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Observations on the Horizontal Bends of Rural Roads Whose Plan Sheets Never Existed

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Abstract

Unlike high-volume roads, for many low-volume country roads, curve advisory speeds cannot be predetermined in office because of the absence of plan sheets. In many places this is solely done by engineers on site using some degree of expert judgment, because conventional use of ball-bank indicators, as well as in-place radius and superelevation measurements for every horizontal curve, are time consuming. This is because of the high number of bends of such low-volume roads, a problem which is not fully acknowledged by many highway authorities. The present paper identifies common irregularities and inconsistencies concerning the horizontal bends of such roads based on the "continually" collected ball-bank data, as opposed to repetitive measurements. Three separate roads, located in the Afyon and Burdur regions in Turkey, each containing several horizontal curves, have been studied (two of them had no sheets of plans). The findings revealed that legal speed limits were inappropriate (even at tangents) and many curves did not have any speed signs, while some had unrealistic values being posted. The method described in this paper introduces a swift and reliable way of collecting information on how a vehicle negotiates these bends, so that problematic bends can be identified and later be revisited for further scrutiny.

Keywords

roadway design, low-volume roads, safety, curves, horizontal alignment, methodologies used for analysis and research of geometric design, speed

Horizontal curves can be described as those sections of roads where tolerable lateral acceleration limits are "put to the test." Although horizontal curves represent only a small fraction of most highways, a sizeable portion of road crashes occur along these sections and the majority are caused by sliding or rollover of vehicles negotiating these horizontal curves (*1*–*3*). Lee reported that fatal crashes are three times higher at horizontal curves when compared with the tangent sections of the same road (*4*). It was also stated that two thirds of deaths happen on horizontal curves of rural roads in the US (*4*). The increased demands placed on the driver and the vehicle that could lead to a wrong choice of speed and trajectory is the main reason behind this problem (*5*, *6*). Based on driving simulator results, Sil et al. studied consecutive horizontal curves and found that driver error in distinguishing preceding and upcoming curves may lead to fatal crashes (*7*). Afghari et al. claimed that horizontal-curve-related accidents can be attributed to the problem of "misunderstanding" the geometry of the unexpected curve ahead (*8*).

Correct design and flawless construction of horizontal curves, therefore, possess a great deal of importance. However, in many places, low-volume roads, such as country or mountain roads, have no sheets of plans. Many of these roads are relatively old and were mostly constructed by following the original topography of the older track of the previous road in place. During their construction, certain engineering decisions, such as superelevation calculations, could only be carried out on-site using preprint nomographs or tables available at the time. These types of road are usually low-volume,

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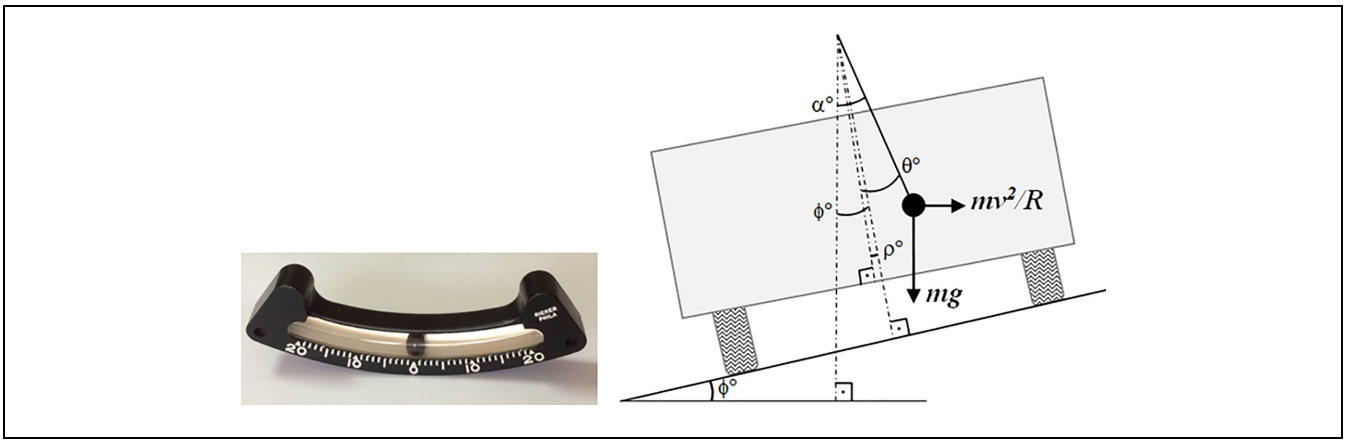

Figure 1. The mechanical ball-bank indicator (*left*) and its pendulum analogy (*right*).
Source: Photo taken by the author.

two-way, two-lane country roads with narrow lane widths, and sometimes with sharp and frequent curves. The tangents between successive curves may be very short. These types of road are made of many compound, broken-back, or reverse curves with disorderly curve-linear alignment. Undertaking an audit, such as a safety check on a particular section of a road or a post-crash investigation, in the absence of plan sheets, knowledge of design, and advisory and operating speeds may become a difficult task. The U.S., for example, suffers from a lack of roadway inventory databases for such roads (*2*). These checks could involve measurements of sight distance, curve radius, superelevation, and so forth. There is no doubt that less costly methods of assessing overall riding comfort and vehicle stability along such roads would be a useful tool for highway agencies before focusing on individual curves for further investigations. This paper aims to ascertain the possibility of continually obtaining some degree of knowledge on lateral discomfort levels over numerous successive bends in a reasonably reliable and inexpensive way, without even stopping the test vehicle, to be able to pinpoint problematic curves quickly.

Throughout this paper, the term "bend" will only be used to refer to the horizontal curves of country roads with no sheets of plans, whereas the term "horizontal curve" will still be used in its common and general use to refer to all road types with and without plan sheets. The paper will first provide a thematic and comprehensive review of existing literature on the employment of ball-bank indicators from various studies. Then, using a mechanical ball-bank indicator, observations will be made on two example country roads and a major highway, located in the Afyon and Burdur regions in Turkey.

Literature

The Ball-Bank Device

There are two types of ball-bank indicator: mechanical and digital. The former is made of a glass curved tube with a small metal ball inside, freely moving sideways within a special liquid (Figure 1). The device is carefully fixed to a test vehicle so that it is perfectly parallel to the vehicle's horizontal axis. Then, the vehicle, too, needs to be perfectly horizontal so that the ball-bank indicator shows 0° when the vehicle is stationary on a level surface (with equal tire pressures).

In order for the ball-bank indicator to show a non-zero value, either the vehicle should be on a superelevated surface, or the vehicle should be traveling along a horizontal curve producing centripetal acceleration. Obviously, a combination of these two cases will also produce non-zero readings, provided that the two cases will not cancel each other out. Superelevation and centripetal acceleration (and the resulting body-roll of the test vehicle) are the only causes of a non-zero ball-bank indicator reading. Centripetal acceleration is also known as "lateral acceleration" among highway engineers for design purposes (*9*).

The digital ball-bank device is powered by the test vehicle's cigarette lighter and can be connected to an on-board laptop computer by a USB port. This device, too, needs to be horizontal during calibration. Since only a mechanical ball-bank indicator was used in this paper, no further information for the digital indicators will be provided here. Existing literature can be consulted for more technical details of the digital ball-bank device (*10–12*).

The magnitude of the centrifugal force acting on the metal ball (Figure 1) is mv^2/R, where, m is the mass of

the ball (in kg), v is the speed of the vehicle (in m/s), R is the radius of the horizontal curve (in m), α is the centripetal acceleration angle (in degrees), θ is the ball-bank reading (in degrees), ϕ is the superelevation angle (in degrees), and ρ is the body roll angle (in degrees). The forces acting on the vehicle are in balance as: $mg\sin\alpha = \frac{mv^2}{R}\cos\alpha$. With $\alpha = \theta + \phi - \rho$ transformation, the same equation becomes: $\tan(\theta + \phi - \rho) = \frac{v^2}{gR}$. If speed is inputted as km/h (V) and the gravitational pull (g) is taken as 9.81 m/s^2, the equation can also be written as: $\tan(\theta + \phi - \rho) = \frac{V^2}{127R}$. Several studies, such as Carlson and Mason, and Echaveguren and Vargas-Tejeda, reported that the body roll angle (ρ) does not exceed 1° in modern vehicles and can be neglected (*13*, *14*). As a result, by ignoring body roll, the tangent of the ball-bank reading is only the algebraic sum of superelevation (in %) and side friction demand. Moreover, if the curve is not superelevated, the ball-bank reading is directly the side friction factor demanded between the road surface and the tires. Another special case is that if the curve in question has "theoretical" superelevation (i.e., the centripetal acceleration is overcome only by superelevation without any side friction supply) and the vehicle is traveling exactly at the critical speed, then the ball-bank indicator shows zero angle. For more interesting implications of the concept of theoretical superelevation, refer to Gunay (*15*).

Side Friction

The term "side friction demand" should not be confused with "side friction supply" which refers to the limiting value of lateral friction factor at the onset of sliding (see *16–18*, for more detailed definitions). The side friction factor used in design of horizontal curves is, therefore, not the limiting friction supplied; it is rather based on the threshold value at which the "side pitch outward" is first noticed by the driver. This is because the roadside environment also plays a role in the selection of a comfortable speed, and is known as the "driver's judgement of incipient instability" (*19–21*). As Elvik claims, drivers select their operating speed based on the road status, not on the road design (*22*). Besides, Donnell et al. state that the American Association of State Highway and Transportation Officials's horizontal curve design is based on limiting the value of side friction to be less than a specified value which is selected based on driver tolerance for lateral acceleration (*9*). Furthermore, it should be remembered that the design side friction factor is itself a function of vehicle speed and reduces with increasing speed. Various similar terms may be found in literature to refer to side friction demand—lateral ratio, unbalanced centrifugal ratio, cornering ratio, or unbalanced side friction—as was reported by Merrit (*21*). Lamm et al. introduced a "utilization ratio" (n), expressed by the ratio of permissible side friction to the maximum side friction, as in: n = (side friction factor utilized / maximum permissible side friction factor) x 100 (*23*). They applied their findings to rural and suburban roads. Later, Lamm et al. introduced three levels of safety criteria to assess accidents on two-lane roads (*24*). These were: 1) the difference between design speed and variations in observed 85th percentile speed, 2) the difference between observed 85th percentile speeds on successive design elements, and 3) the difference between side friction assumed and side friction demanded at the 85th percentile speed. Bonneson et al. formulated the relationship between side friction angle (in radians) and ball-bank reading (in degrees) as: $ball - bank\ reading = 59.97 \times side\ friction\ angle$, which passes through the origin of an x-y coordinate system, with an R^2 value of 0.69 (*25*).

The typical use of the ball-bank method is for determining advisory speed limits for horizontal curves. Even if the road has a set of plan sheets, from which curve radius, design speed, side friction factor selected, and superelevation rates can theoretically be retrieved, the ball-bank indicator may still be used to assess the current status of the road together with the actual operating speeds (usually taken as the 85th percentile speed) and the effect of the roadside environment. Settling of the road base or deformations on the pavement surface through time may cause superelevation to malfunction. Russo et al. defined the term "operating speed" as the speed at which drivers travel on dry and paved roads in free-flow conditions during daylight hours (*26*). All the literature reviewed here is based on studies conducted on paved roads. For speed limits and vehicle stabilities on the curves of unpaved roads, see, for example, Jones and Ksaibati (*27*).

International Interest

Fitzpatrick et al. drew attention to the liability concerns arising when posted speed limits exceed design speed (*28*). They conducted a mail-out survey among various agencies and districts in the U.S. to clarify the relationship between design speed, operating speed, and posted speed using the ball-bank device. Krammes critiqued the concept of design speed in the U.S., Europe, and Australia (*29*). In the U.S., by the end of the century, nearly 90% of the states started to facilitate the ball-bank method for the abovementioned purposes (*4*). Similarly, Russo et al. studied Italian and Serbian roads and found two types of driver behavior when negotiating horizontal curves: 1) those who decelerate when approaching the middle of the curve and accelerate afterwards (which is confirmed by Dhahir and Hassan), and 2) those who

decelerate over the whole curve length (*26*, *30*). Dinh and Dung studied a series of horizontal curves in Vietnam where advisory speed signs do not exist, instead the country imposes fixed 60 km/h speed limits on the 10 curves studied by Dhahir and Hassan (*30*, *31*). Based on ball-bank indicator results, their findings revealed that the "real" speed limits should be 5–25 km/h lower than this fixed value. Although no other research has confirmed this yet, García-Ramírez and Aguilar-Cárdenas reported different comfort perception by the occupants of a vehicle when negotiating left and right turning curves in the country of Ecuador (*32*). They claimed that left curves had higher lateral accelerations than right curves for speeds between 50 and 80 km/h. Aminfar et al. studied 10 reverse curves of mountain roads in Iran and found that the road's longitudinal grade had a positive relationship with the lateral friction demand (*33*). Echaveguren and Vargas-Tejeda proposed an analytical method for estimating advisory speed based on lateral acceleration and consistency assessment of single horizontal curves in Chile by comparing Preisler's and Koorey's models (*14*, *34*, *35*). As summarized here, the issue of negotiating horizontal curves has aspects and features which attracted research interest around the world. The present paper, too, aims to observe the situation, with particular reference to selected Turkish rural roads with no plan sheets.

Curve Signage

The ball-bank methodology found another useful application area in horizontal curve signage, such as the warrants and frequencies of delineators at the approach to and along the highway curves (*25*, *36*, *37*). Using ball-bank indicators, Voigt et al. studied dual advisory signing on freeway connectors for light and heavy vehicles, as trucks can roll over on freeway ramps when traveling as little as 5 mph over the design speed (*38*, *39*). It should be remembered that horizontal as well as vertical curve warning treatments are always cost-effective, and ball-bank indicator tests may be the ideal, simplest approach, as Persaud et al. points out (*40*). Avelar and Dixon developed a function to model the "expected" safety effect of advisory speed signs and compared it with the limits that are based on ball-bank tests, claiming that their model performed better, although no further research, to date, has confirmed this (*41*). The issue of ball-bank indicator limits will be discussed in more detail below.

Comfort Limits

If a certain limiting ball-bank angle is reliably established, then, for a given radius, superelevation, and side friction demand, a safe speed to negotiate a horizontal curve can easily be determined. Research has already been conducted for this purpose and found that, for decreasing test speeds, ball-bank indicator limits increased, as drivers were more willing to tolerate higher values of lateral acceleration, and they felt more confident of vehicle control at lower speeds. For instance, Chowdhury et al. recommended 20° ball-bank limit for speeds below 48 km/h, 16° for speeds between 48 and 64 km/h, and 12° for speeds above 64 km/h (*42*). Carlson and Mason reported a slightly different range as 16° for speeds of 48 km/h or lower, 12° for speeds between 48 and 80 km/h, and 9° for speeds of 80 km/h or above (*13*). The *Manual on Uniform Traffic Control Devices for Streets and Highways* (U.S. DOT) recommended 16° for speeds of 32 km/h or lower, 14° for speeds between 40 and 48 km/h, and 12° for speeds 56 km/h or higher (*43*). Hillderbrand and Lewis suggested that the limits should be raised in the short term: 16° for 30 km/h or lower, 14° for 50 km/h, 12° for 70 km/h, 10° for 80 km/h or above, and, for all other intermediate values, 1° adjustment for every 10 km/h speed change (*44*). Figure 2 summarizes these findings in a graphical format. It is evident from the figure that research agrees that, as speeds increase, tolerable ball-bank readings drop. The upper side of these curves implies discomfort and risks of sliding or rollover.

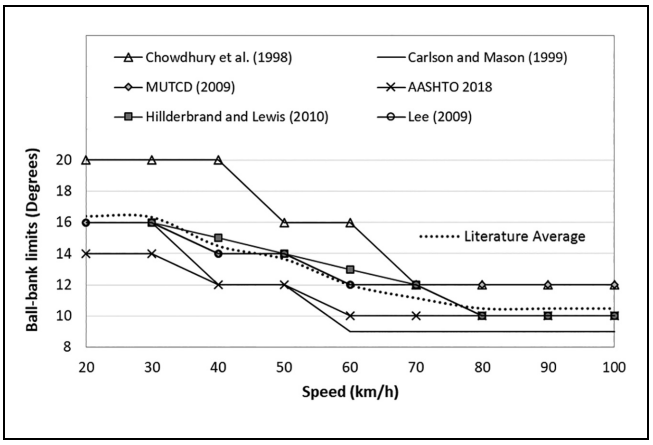

Figure 2. Key literature on ball-bank comfort limits.
Note: AASHTO = American Association of State Highway and Transportation Officials; MUTDC = *Manual on Uniform Traffic Control Devices for Streets and Highways* (*43*).

Radius Estimation

As was previously mentioned, the radius of a horizontal curve is one of the parameters (together with superelevation, speed, and side friction demand) to be known in studies requiring on-site investigations. Researchers, therefore, have addressed the issue of obtaining

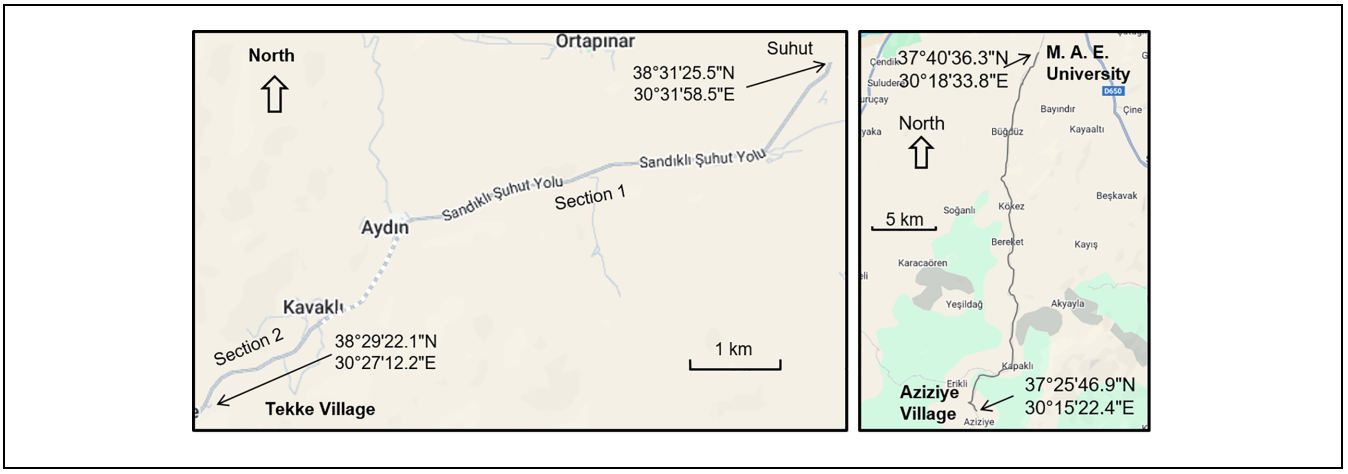

Figure 3. The first data collection site comprising two sections (*left*), and the second data collection site (*right*).
Note: M.A.E. University = M. Akif Ersoy University campus.
Source: Google Maps.

(measuring) curve radius in as practical a way as possible. Although no further details will be discussed in the present paper, literature such as Carlson et al., Ibraheem and Janan, and Mascio et al. may be consulted in this respect (*45–47*). Similarly, efficient ways of measuring superelevation have attracted research interest, such as Tsai and Ai, who developed an automated, low-cost intelligent safety assessment tool for horizontal curves using ball-bank indicator results (*12*).

Other Factors

There are other factors which influence the friction demand, such as tire size (contact patch), composition, and tread wear. Also, road surface materials, International Roughness Index (IRI), and pavement skid resistance play a role on the lateral friction supply. Moyer and Berry, for example, stated that, on dry concrete surfaces, the skidding side friction limits were between 1.01 and 0.89, depending on speed (*48*). On wet pavements, it ranged from 0.78 to 0.64, again depending on speed. Later, Fancher et al. found similar figures (*49*). Wong reported that, for worn tires, the maximum and sliding friction decreases by 30% between 20 and 60 mph (*50*). Lateral friction at the tire-pavement interface is about 7.5% less than longitudinal friction, based on friction ellipse, which was earlier described in detail by Gillespie (*51*, *52*). Gunay and Woodward discussed IRI and lateral position of vehicles on the road with particular reference to Northern Irish urban roundabouts (*53*). They stated that, depending on the type of bituminous material, traffic, and environmental conditions, properties such as skid resistance, texture depth, and noise will change, eventually reaching a stage where further action is required.

Data

Sites and Settings

Three different data collection sites in Turkey were selected for the observations. The first two were low-volume rural roads constructed without any plan sheets. The third site, a divided highway, constructed with plan sheets, was chosen as an additional site, only to be able to see the situation on a high-volume road. While site 1 had no curve speed signs on the 42 bends studied, eight bends (of many) on site 2 had curve speed signs erected because of curvature per se. Site 1 was in the Afyon region on the Suhud-Sandikli road, composed of two separate sections (Figure 3*a*) and the second site was in the Burdur region between M. Akif Ersoy University campus and Aziziye village (Figure 3*b*).

Data were collected on all sites during daylight hours and the weather was dry. Any work carried out to establish limiting skid resistance values are conducted on wet surfaces using standard testing procedures. However, the main purpose of the present work, rather than measuring absolute coefficient of friction values, was simply to identify inconsistencies between the bends studied and to position the findings with respect to the ball-bank literature averages, which were obtained in dry weather conditions. The friction factors used in current literature do not reflect the maximum safe speed but, rather, an average comfortable speed (*46*). As was mentioned above, modern cars on dry pavement are capable of generating friction coefficients of 0.65 and higher before skidding. Thus, a curve designed, for example, for 70 mph could be driven well over 100 mph before the vehicle skidded out (*46*).

The test vehicle used in the study was a saloon car (Toyota Corolla, 2020 model) with a digital speedometer



Figure 4. "Curve ahead" signs in the approach of a bend (site 1).
Source: Photo taken by the author.

and a built-in navigation screen on-board. Before commencing each test, in the same way as for any other study using a ball-bank indicator, the tires were checked by an expert garage to make sure that all four tires had equal pressures. Always the same garage was visited throughout the study for this purpose. Also, before each test, the vehicle was parked on a level surface in various directions to see if the ball-bank indicator shows 0° readings in every direction on the same spot. A tripod (and a video camera) was fixed in the car in the middle, just behind the front seats. This camera was able to concurrently capture 1) the car's speedometer, 2) the dashboard navigation screen (the car's real-time position on a map), 3) the ball-bank device mounted on top of this screen, and 4) the outside view from the windshield.

In all test runs, the vehicle was driven by the researcher himself to maintain uniformity throughout the study. He drove the test vehicle always at his maximum comfortable speed (where sight distance, etc., permit). Therefore, the findings discussed in the paper reflect borderline features as much as possible. Legal speed limits were ignored for the sake of research. The researcher paid attention to keeping the vehicle in the middle of the lane all the times as much as possible, by avoiding oversteering and over correcting. Sudden speed changes and harsh braking were also avoided. After the tests, the video files were transferred to a PC in the office and analyzed.

For the entirety of the road traveled at the first site, no bend had speed signs. Instead, some bends had "curve ahead" signage (Figure 4) and the rest had no warning signs at all. In Figure 4, as an example, it is possible to see what the in-vehicle camera views: the digital speedometer (showing 78 km/h), the ball-bank device (showing + 1° banking, probably because of the normal cross-fall at tangent), and the navigation screen (showing the location of the test vehicle on the map). None of the sites studied had road markings showing any speed limits. Sites 1 and 2 had relatively vague longitudinal lane lines to mark both edges of the roadway. Site 3 had more visible side and center lines, and railings and delineators, but, again, it did not have any surface markings for the purpose of displaying speed limits.

The video files were analyzed second-by-second by pausing the recording at the beginning of each second (using video player software with time precision). For instance, for a 10 min recording, 600 sets of readings were obtained, each set containing a ball-bank reading and a corresponding speedometer value.

To exclude village passings from the data (i.e., to eliminate non-rural portions of the road), site 1 was split into two sections, that is, the Suhud–Aydin section (5.1 km), and the Kavakli–Tekke section (1.3 km). The legal speed limit was 90 km/h.

Use of Speedometer

The values displayed on the test vehicle's own speedometer (dashboard speed) were used for the speed data. It should be noted that vehicles' speedometers are configured to exaggerate speeds by a small amount when compared with the actual (true) values, a practice adapted by car manufacturers for better safety. This discrepancy may change from vehicle to vehicle. Readers wishing to compare the speed readings of the present paper with other research findings (obtained by measuring speeds from outside their test vehicle) may prefer to know how much deduction should be made for more universal comparisons.

For this reason, a calibration study using a global positioning system (GPS) method was conducted by the test vehicle, in which the vehicle was driven on a flat and straight highway between Sandikli and Keçiborlu towns (Afyon-Isparta highway) at constant speeds ranging from 45 to 131 km/h in increments of 1 km/h using the vehicle's cruise control. While the vehicle was being driven, a cell phone's GPS was used to obtain the speed of the vehicle. This was recorded by an in-vehicle camera, which was also able to capture the vehicle's speedometer. The differences between the vehicle's speedometer and the GPS values (Δ) are displayed in Figure 5. It has now become possible to state that, to best reflect the true speed of the test vehicle used in the present study, deductions from the speedometer values should be about 2 km/h for low speeds (below 70 km/h), about 3 km/h for moderate speeds (70–90 km/h), and 4 km/h for high speeds (90–100 km/h). Or, if the reader prefers a continuous linear relationship, using the least square line fit within this speed range, a linear

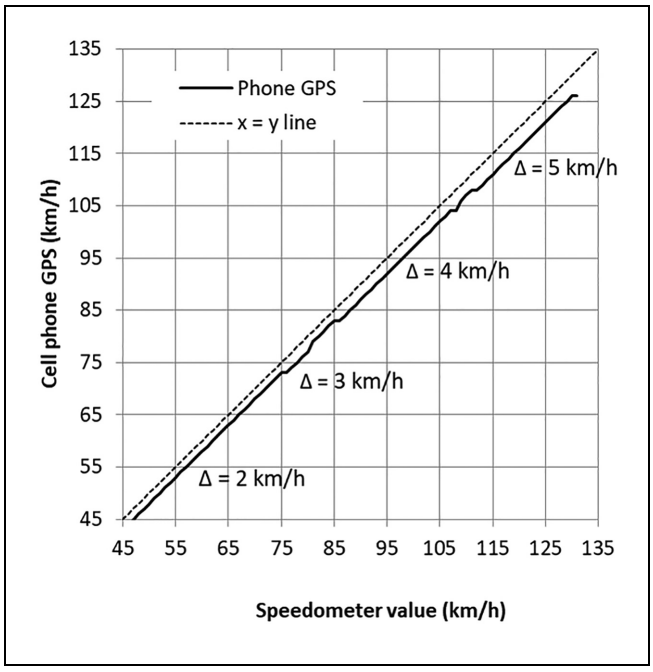

Figure 5. The gap between the vehicle's speedometer values and the global positioning system (GPS) measurements.

equation may be recommended with an R^2 value of 0.83: discrepancy(Δ) = (0.03 × speedometer value) + 0.23.

Findings

Site 1

Firstly, speed profiles and corresponding lateral accelerations were studied for the two sections of Site 1. For the lateral accelerations, the mechanical ball-bank device, described above (in the Literature Review), was facilitated and the readings were obtained by analyzing the recorded video files in office. Figure 6 shows this relationship, where the left vertical axis is the ball-bank readings and the right vertical axis is the speeds. It should be noted that negative ball-bank readings in all diagrams of the paper refer to right-turning curves and positive readings refer to left turnings. Four peaks in the top diagram of Figure 6, *a–d*, deserve particular attention as they exceed ± 10.5°, which is an average recommended ball-bank limit given in literature for 90 km/h speeds (see Figure 2). When similar analyses are carried out for the second section of site 1, the bottom diagram of Figure 6

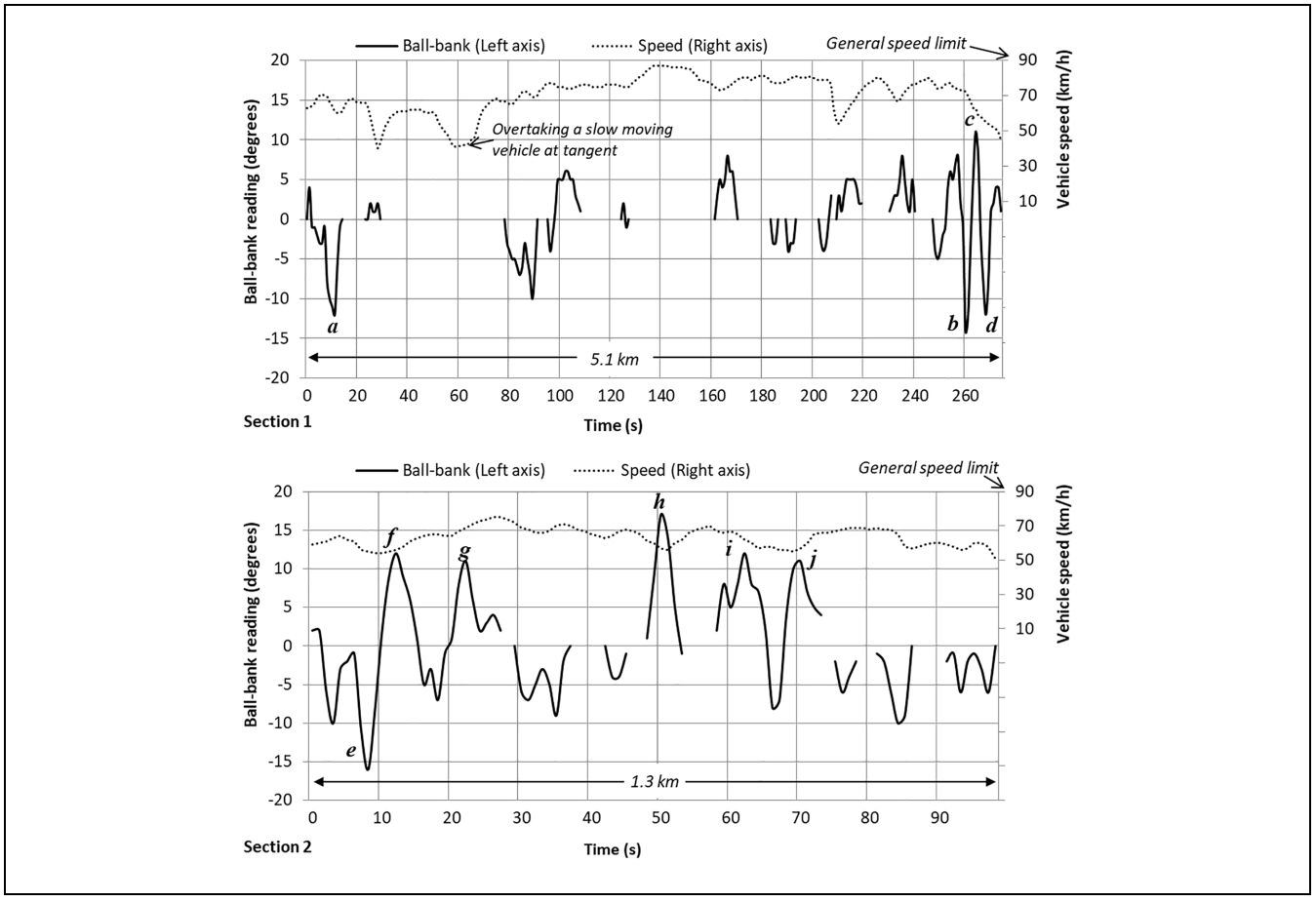

Figure 6. Ball-bank readings and corresponding dashboard speeds with critical peaks, labeled ***a*** to ***j*** (site 1), for section 1 at the top and section 2 at the bottom.

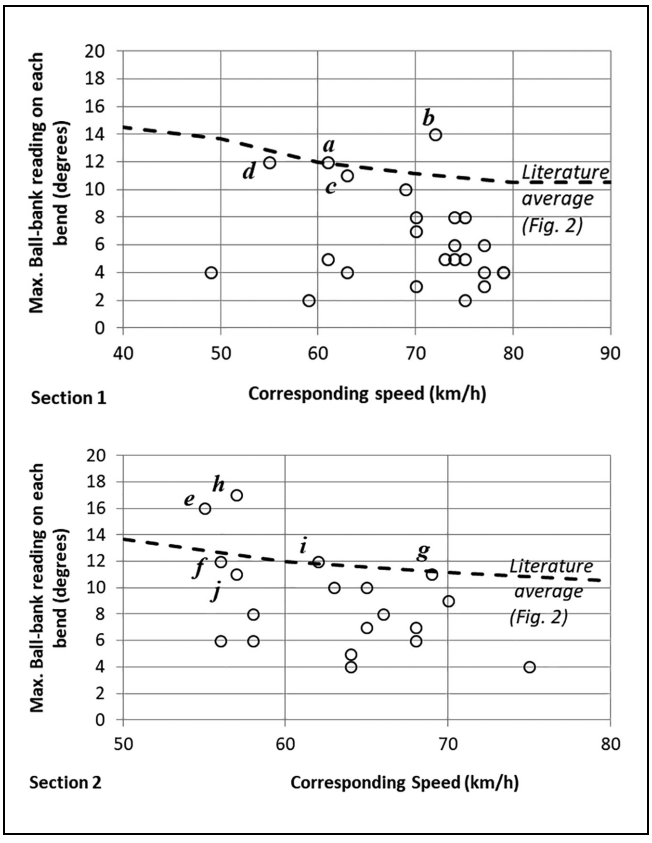

Figure 7. Maximums of ball-bank readings against speed (with the same peaks as Figure 6), for Section 1 at the top and Section 2 at the bottom.

is obtained, where six peaks with particular importance (***e*** to ***j***) are shown. In all these diagrams, whereas the speed profile is made continuous, the ball-bank readings are made discontinuous for clarity purposes by excluding the readings at tangent sections.

In association with Figure 6, to be able show how these observations relate to the comfort limits (Figure 2), the maximums of ball-bank readings (converted to absolute values) are displayed against corresponding speeds (Figure 7). The same special peaks are shown again in Figure 7.

In all of the special peaks (***a*** to ***j***), the $\pm$ 10.5° cut-off limit is exceeded by speeds of lower than 90 km/h. Peaks ***a***, ***c***, and ***d*** are close to the literature average curve but remember the road has a 90 km/h speed limit and these peaks reached about 12° ball-bank at much lower speeds. Similarly, Peaks ***f***, ***g***, ***i***, and ***j*** are very close to the literature average curve, but, again, the ball-bank values of about 12° were achieved when the vehicle was traveling at speeds of only 55–70 km/h. Therefore, for the bends corresponding to these peaks, speed signs of 80, 70, or even 60 km/h may be an appropriate remedy. It should be noted that none of the bends on this road had speed signs. But, of course, the exact value of advisory speeds will be subject to further scrutiny of these bends. For example, repetitive ball-bank tests at various speeds, as described in ball-bank code of practice documents (if the country had adapted these codes) may be one method to apply. Especially, peaks ***b***, ***e***, and ***h*** in Figure 7 are off the literature average, which means unacceptable (uncomfortable) lateral acceleration even at speeds as low as 55–57 km/h. Other data points may also go over this limit with increasing speeds, but it is not possible to speculate this by only looking at these diagrams, and this is left for further work.

It is also interesting to see in these figures that, although the researcher drove the test vehicle as fast as he could, he rarely approached (or exceeded) the legal speed limit of 90 km/h in both sections (including the tangent portions of the road). This shows that other factors, such as sight distances or lane widths, must have played a role in deciding driving speeds. Based on these observations, it may also be possible to criticize the current legal (general) speed limit on this road even at tangents, as it seems to be too high (again, subject to further analysis). However, it was satisfying to reveal that drawing these diagrams using such a simple method enables engineers to observe whether or not lateral-acceleration-based discomfort was fully responsible for not achieving high speeds on these country roads.

Site 2

The second data collection site was in a different area under the ruling of a different local authority (but within the same jurisdiction). The road studied was about 32 km long and had numerous bends, some of which had speed signs (unlike site 1). These speed signs can be grouped under two categories: 1) those signs erected because of the curvature ahead (which is the subject of this paper) and 2) those erected for other reasons such as visibility restrictions along the curve. In Figure 8, the first group bends are shown. Three bends in this group (**1**, **7**, and **8**) had 30 km/h and five bends (**2**–**6**) had 50 km/h speed signs, as also shown at the top of the diagram. The width of each mark in the horizontal axis of Figure 8 denotes 5 s of duration. Because the length of the road studied was too long, it was not practical to display all readings here. Instead, only the bends studied in the first group were shown in the diagrams below in a discontinued fashion.

Like the analysis of the first site, maximum ball-bank readings of each bend were recorded against the corresponding dashboard speeds (Figure 9). As can be seen from this figure, there is very poor consistency among the bends with regard to the advisory speed values. For example, according to the literature average (Figure 2), for 30 km/h speeds, 16.3° may be considered as the

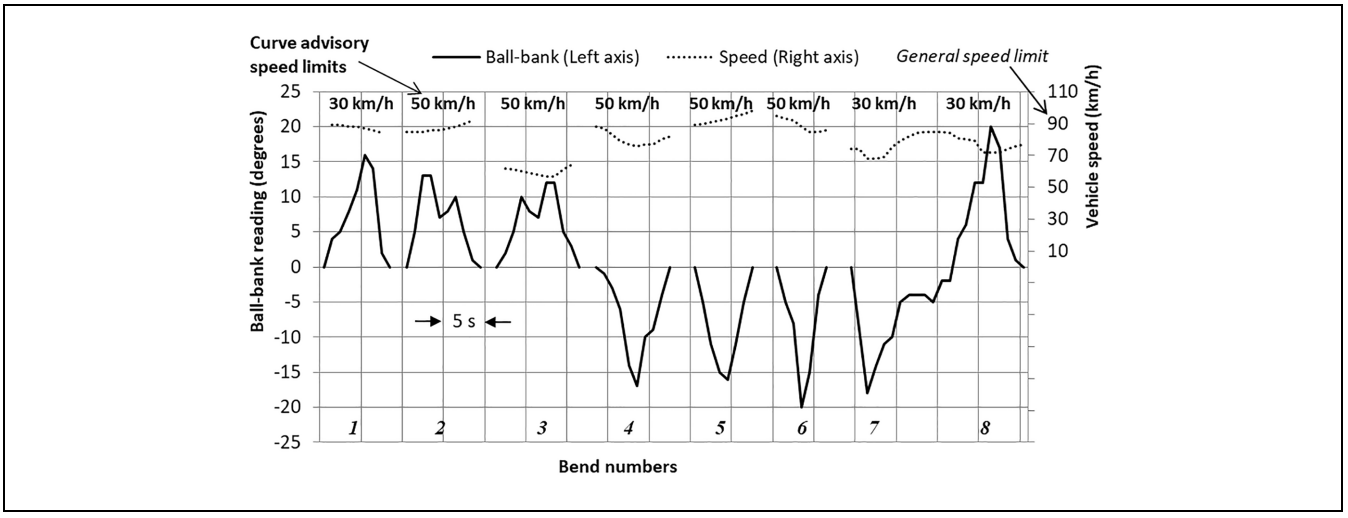

Figure 8. Bends with speed signs (erected because of curvature) along site 2.
Note: hollow data points = bends with 50 km/h speed signs; solid data points = bends with 30 km/h speed signs.

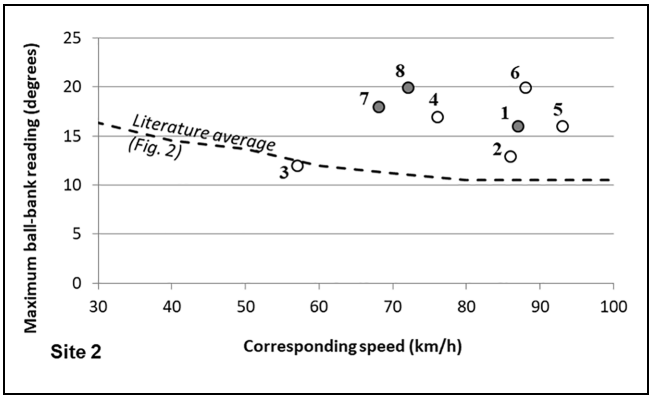

Figure 9. Maximum ball-bank readings.
Note: hollow data points = bends with 50 km/h speed signs; solid data points = bends with 30 km/h speed signs.

recommended ball-bank limit. However, the test vehicle produced this amount of lateral discomfort when negotiating bends ***1***, *7*, and ***8*** at speeds about 70 km/h or above. As one extreme example, the data point ***1*** represents a ball-bank reading of 16° as a result of about 87 km/h speed when negotiating a curve with a 30 km/h speed sign. This clearly shows the inappropriate choice of these signs along this road.

Similar observations can be made for those bends with 50 km/h speed signs (bends **2**–**6**). Data point **3** can be considered as a bend with an appropriate speed sign, since this data point is not far from the speed-ball-bank combination of 50 km/h and its literature limit of about 14° ball-bank reading (from Figure 2). The other data points, especially ***2***, ***5***, and ***6*** show that the test vehicle was driven at those speed levels which produced uncomfortable lateral accelerations. Since the radii and superelevation values are unknown for these bends, further tests should be undertaken to see whether acceptable ball-bank readings would have been obtained, if the vehicle had been driven at 50 km/h on these particular bends.

Site 3

Finally, to be able to see what the above approach can reveal for a high-volume dual carriageway (constructed with plan sheets), a set of additional data was collected on a state highway (let this road be called site 3). The same test vehicle was driven in the fast lane of this dual carriageway along a 6.7 km mountainous section, which contained 11 horizontal curves. Site 3 is located between Burdur and Celtikci towns (southbound) with a legal speed limit of 110 km/h. Only one horizontal curve (i.e., curve ***9***, between 173–191 s in Figure 10) had a speed limit of 50 km/h, because of a crossroad in the middle of the curve. The map given at the bottom of the diagram shows these 11 curves together with the times, in association with the horizontal axis of the top diagram. Using the same method, vehicle speeds against ball-bank readings are displayed in Figure 10. Since the data were collected along a mountainous stretch of the road, it was rarely possible to exceed the legal speed limit of 110 km/h even in the fastest (left) lane.

Problematic curves can easily be identified in Figure 11. While the ball-bank readings for curves ***1***, ***8***, and ***11*** did not exceed about 10° for speeds at and beyond the legal limit (i.e., 110 km/h), curve *7*, for example, produced 18° of ball-bank reading for a similar speed value. Curves such as ***3***, ***5***, ***6***, and ***9*** gave high ball-bank readings even at speeds much lower than the legal limit. Curves ***2*** and ***4*** gave relatively more acceptable values. Based on

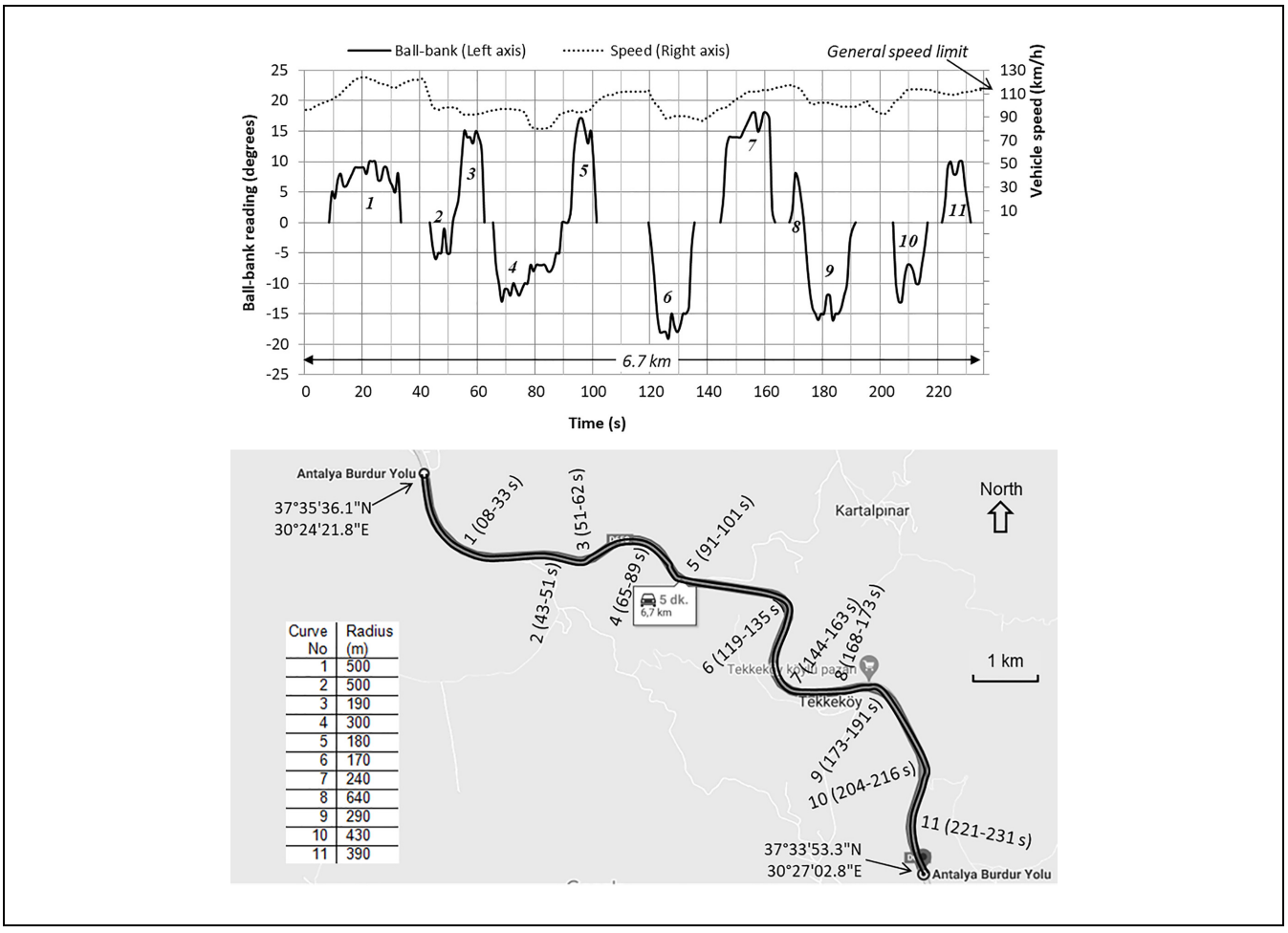

Figure 10. Ball-bank readings and corresponding instantaneous (dashboard) speeds (the top diagram) on a divided two-lane highway (the bottom diagram, Google Maps), constructed with sheets of plans (site 3).

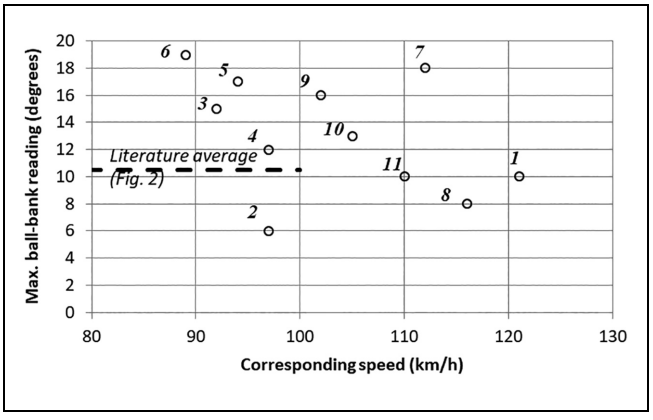

Figure 11. Negotiating the horizontal curves of a mountainous dual carriageway by the test vehicle (site 3).

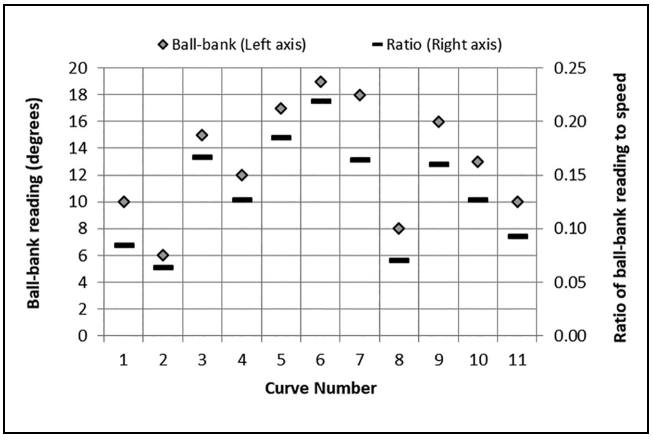

Figure 12. Variations in the ratio of ball-bank readings to the corresponding speeds (site 3).

these preliminary observations, it is suggested that engineers should primarily concentrate on curves ***3***, ***5***, ***6***, *7*, and ***9***. These curves may require advisory speed signs.

Finally, the ratios of ball-bank readings to the corresponding speeds have been computed for these curves (Figure 12). While curve ***2*** had the smallest gap (between

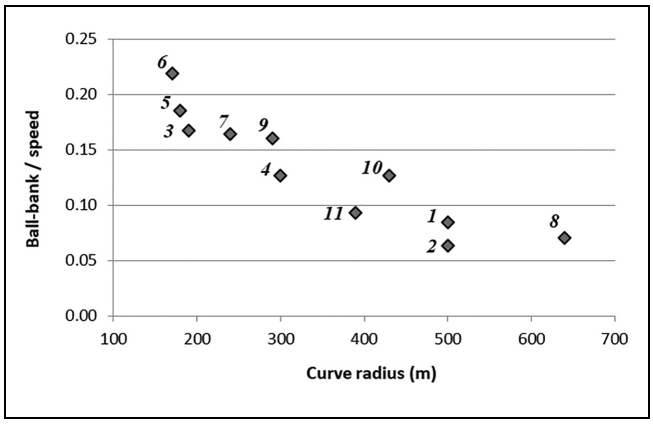

Figure 13. The ratio of ball-bank reading to the corresponding speed for various radii (site 3).

the ball-bank reading and the ratio in question), curve *7* had the largest differentiation.

Since this road had plan sheets, radii information was available, retrieved from the Highways Agency, Antalya (Figure 10). It is an expected feature that, with increasing radius, the ratio of ball-bank reading to the corresponding speed should have a declining trend (Figure 13). This is because, as curves become sharper (with small radii), maximum attainable speeds drop and ball-bank readings become bigger. This scrutiny is a new approach and may merit enhancements by future research into the rate at which this declining trend may become a useful tool, when various sites, roads, drivers, or vehicles are to be compared in this respect.

Concluding Remarks

Although ball-bank indicators are widely used in the U.S. and in some other countries, many highway agencies around the world do not require their use in setting or assessing curve advisory speed limits. In Turkey, for example, this device is unknown, and its use is not a legal requirement. As a result, curve advisory speed limits are calculated in office, as radius, superelevation, and design speeds are known from the sheets of plans for high-volume roads. However, roads with no plan sheets are subject to serious safety risks. Because there is not a practical method of determining curve advisory speeds, engineers may be reluctant to assess every bend, because of certain difficulties mentioned in the paper. Therefore, many bends are left with no speed signs or with inappropriate values being displayed. This paper aimed to draw the attention of authorities from other countries as well, with similar practices, to the problem, by first showing how vehicles negotiate curves in country roads and then describing a cost-effective way of obtaining initial information for such roads to be used for further investigations, if desired. Since this paper provides a detailed description of the methodology, the work can easily be replicated by low-volume road managers.

Author Contributions

The author confirms sole responsibility for the following: study conception and design, data collection, analysis and interpretation of results, and draft manuscript preparation.

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