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Varying Levels of Lateral Acceleration Supplied on Interchange Loops with No Speed Signs for Guidance

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Abstract

Highway interchanges should not be left "unattended" when it comes to signage, but in many countries such key locations lack adequate speed limit signs. Therefore, drivers, who normally expect "accustomed" lateral acceleration levels when negotiating the loops of interchanges, have to choose correct speeds on their own. The paper reveals the extent of this problem using ball-bank data collected from four Turkish cloverleaf interchanges. Three criteria are introduced: 1) first maximum, 2) rate of change of radial acceleration, and 3) average riding comfort along the loops. The following features are scrutinized: in criterion 1, the first maximum ball-bank reading for each loop against its corresponding speed; in criterion 2, how quickly the lateral acceleration develops as the test vehicle enters and exits a loop; and in criterion 3, the average values of ball-bank readings as the test vehicle travels along the loops. To maintain the same level of lateral comfort, the test vehicle had to experience about 6 km/h speed variation among the loops of the same interchange, and more than 15 km/h speed variation among the interchanges studied, as far as criterion 1 is concerned. In relation to criterion 2, the test vehicle underwent a faster ball-bank differential when entering a loop than it did when exiting. With regard to criterion 3, about 4 km/h speed variation among the loops of the same interchange and nearly 16 km/h speed variation among the interchanges studied were recorded. The methodology developed in this paper can easily be adapted for similar objectives to study the loops of interchanges in other countries.

Keywords

roadway design, performance effects of geometric design, curves, interchanges and freeways geometric design, intersections geometric design, speed, superelevation

A sizeable portion of road crashes occur along horizontal curves and the majority are caused by sliding or rollover of vehicles negotiating these curves (*1–3*). Fatal crashes are three times higher at horizontal curves compared with the tangent sections of the same road (*4*). Additional tasks that need to be performed by the driver along the curves that could lead to a wrong choice of speed may be the main reason behind this problem (*5*, *6*). Horizontal-curve-related accidents may also be attributed to the problem of misinterpretation of the geometry of the curve ahead (*7*, *8*).

Interchange projects, in particular, cost highway agencies large amounts of money. Design decisions on such investments, therefore, should be made wisely (*9*). This also means that the loops of interchanges should comply with the standards of proper signage.

It should be noted that, in this paper, the term "loop" is used to refer to those cloverleaf-like parts of the interchanges which allow 270° rotational movements, whereas the terms "ramp" or "connector" are only used to refer to the connecting links to allow about 90° movements at these interchanges.

Interchanges possess certain safety consequences in design, such as types of connecting ramps, radii, and superelevation (*10*). Thus, flawless design, construction, and operation of horizontal curves, interchange connectors, and loops become vital in highway engineering.

Even if curve radii, design speeds, side friction factors, and superelevation rates can be retrieved from the plan sheets of the road, the ball-bank indicator is still used to

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assess the current status of the road together with the actual operating speeds and the effect of the roadside environment. In the U.S., nearly 90% of the states facilitate the ball-bank method for such purposes (*4*). Settling of the road base, deformations on the pavement surface through time, or even design/construction mistakes may cause superelevation to malfunction. When posted speed limits exceed design speed, legal liability issues may arise and, for this reason, Krammes critiqued the current design speed practice in the U.S., Europe, and Australia (*11*, *12*). Using ball-bank methodology on 10 horizontal curves in Vietnam where fixed 60 km/h speed limits are imposed, it was found that real speed limits should be 5–25 km/h lower than the fixed value (*13*). Different comfort perception by the occupants of a vehicle was observed when negotiating left- and right-turning curves in the country of Ecuador (*14*). Echaveguren and Vargas-Tejeda proposed models for estimating advisory speeds in Chile by comparing Preisler et al.'s and Koorey's models (*15–17*).

Mechanical ball-bank indicators are made of a glass curved tube with a small metal ball freely moving sideways within a special liquid. The device is fixed to a test vehicle (horizontal when stationary) so that it is perfectly parallel to the vehicle's horizontal axis. In order for the ball-bank indicator to show a nonzero 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 nonzero readings, provided that the two cases do not cancel each other out (*18*). It should be noted that highway engineers prefer to call "centripetal acceleration" "lateral acceleration" or "radial acceleration" in road design practice (*19*). These three terms are used interchangeably in this paper. Superelevation and centripetal acceleration (and the resulting body-roll of the test vehicle) are the only three causes of a nonzero ball-bank indicator reading. It was reported that the body roll angle does not exceed 1° in modern vehicles and can be neglected (*15*, *20*). In the present paper, only a mechanical ball-bank indicator was used in the study and no information for the digital indicators is provided here. Existing literature can be consulted for more technical details of the digital ball-bank devices (e.g., *21–23*).

After providing a comprehensive review, Gunay summarized the findings of previous ball-bank research, which recommended certain comfort limits, and introduced a "literature average curve" (Figure 1) (*18*). To recap the most well-known ones here, Chowdhury et al. recommended 20° ball-bank limit for speeds below 48 km/h, 16° for speeds of 48–64 km/h, and 12° for speeds above 64 km/h (*24*). Carlson and Mason recommended a ball-bank reading of 16° for speeds of 48 km/h

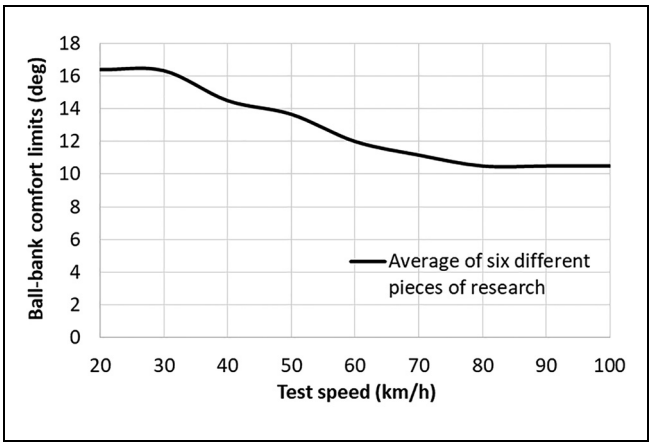


Figure 1. Ball-bank literature average curve.
Source: Adapted from Gunay (*18*).

or lower, 12° for speeds of 48–80 km/h, and 9° for speeds of 80 km/h or above (*20*). The U.S. Federal Highway Administration's *Manual on Uniform Traffic Control Devices for Streets and Highways* recommendation was the ball-bank angles of 16° for speeds of 32 km/h or lower, 14° for speeds of 40–48 km/h, and 12° for speeds of 56 km/h or higher (*25*). Hillderbrand and Lewis stated that the following ball-bank indications should not be exceeded: 16° for speeds of 30 km/h or lower, 14° for 50 km/h, 12° for 70 km/h, and 10° for 80 km/h or above (*26*). It was also reported in the literature that the friction used on horizontal curves is limited more by driver comfort than by the limits of the tire-pavement interaction (*24*). Previous literature all agreed that, for decreasing test speeds, the ball-bank indicator limits increased. This could be because of increasing lateral friction factor with decreasing speeds. In other words, higher side friction values can be tolerated for lower speeds because of less severe consequences of driver errors. This "driver's judgement of incipient instability" is associated with driver discomfort, as correlated with the centrifugal force sensation (*27*).

The ball-bank methodology has been used in horizontal curve signage for many years (*28–30*). Voigt et al. studied dual advisory signing on freeway connectors for light and heavy vehicles in general, and, in particular, Ervin et al. stated that trucks with rollover thresholds of 0.3 g can roll over on freeway ramps when traveling as little as 8 km/h over the design speed (*31*, *32*). Horizontal as well as vertical curve warning treatments were always cost effective and ball-bank indicator tests may be the ideal simplest approach (*33*). Janson et al. estimated that about one-fourth of freeway truck crashes occur at ramps (*34*). Garber et al. emphasized the importance of posted advisory speeds on ramps, and Avelar and Dixon developed a function to model the "expected" safety effect of

advisory speed signs and compared them with the limits that are based on ball-bank tests (*35*, *36*). Setting speed limits is already a difficult and complex task in all countries. A comprehensive report by PIARC, concerning human factors and perception of road elements, defined the term "credible speed limit" as the speed value that is consistent with the expectations of the drivers, physical restrictions, and acceptable behavior of all road users (*37*). The report presents the findings of 30 case studies around the world. Dadashova et al. reported that on freeway ramps the speed choice is a complex process, and, as Monyo et al. claimed, advance warning about interchanges could help reduce errors committed especially by older drivers and improve their safety (*38*, *39*). Johari et al. stated that the crash risk near entrance ramps in consideration of speed differential represents an opportunity for further research (*40*).

The next section will state the problem and set the objectives of this paper. Then, the data collection steps will be explained, followed by analyses and key findings. The last section will be the conclusion and recommendations.

Need for Research

In many countries it may be common practice to underprovide mandatory or advisory speed limit signs in and around highway interchanges. As a result, drivers are left with "unaided" speed decisions when negotiating the loops of such interchanges. Thus, correct and consistent loop geometry (i.e., properly chosen radius-superelevation combinations) gains big importance, so that, when drivers arrive at such locations, based on their driving experience before that particular intersection, they should be able to choose a reasonably comfortable speed against "expected" and "accustomed" radial acceleration. The main objective of this paper, therefore, is to reveal the extent of this problem (i.e., the question of how similar are the radial accelerations among the loops of the same interchange and also among the selected interchanges within the same country). The second aim is to demonstrate how such checks can be carried out using the methods developed in this paper, so that further research can enhance and establish thresholds for consistency. Similarly, practitioners on site can identify the loop that stands out from the rest of the loops, using the approach developed. In this paper, observations were conducted on four example interchanges using the ball-bank indicator, which is an ideal device that can directly measure the resultant and combined effect of speed, superelevation, and curve radius.

Data Collection Sites

For the observations, four different data collection sites were selected and named as A, B, C, and D (Figure 2). For readers to be able to locate these data collection sites on a map, the map coordinates of the centers of each intersection are also provided in the figure. The loops are numbered anti-clockwise from 1 to 4 in each intersection. Intersections A and B were in the Afyon region, whereas intersection C was near Ankara, the capital of Turkey. Intersection D was in Antalya. Data were collected on all sites during daylight hours in dry weather conditions.

All four intersections represent a (non-motorway) cloverleaf layout connecting suburban or rural dual carriageways under the ruling of Turkey's National Highways Agency. Ramps and loops are different from other highway curves in that they sometimes connect two links with different speed limits. Thus, acceleration or deceleration are expected to occur along the curve and/or along the acceleration or deceleration lanes immediately before or after these facilities. This issue is normally handled by choosing correct radius and superelevation combinations and by erecting speed limit signs before these ramps and loops. Even if the two links to be connected have the same speed limit, sharp curvature of the loops requires careful driving. In the absence of sufficient speed signs, drivers tend to adjust their travel speeds according to their lateral discomfort expectations from previous interchange negotiations in the vicinity. The interchanges studied in the paper had almost non-existent (or inadequate) signage, as shown in Figure 3. The national speed limits of the links (but not necessarily posted in the vicinity of these interchanges) are shown in rectangular boxes in the figure.

As can be seen in Figure 3, none of the loops of site A had speed signs, leaving the correct choice of speed to negotiate the loops solely to drivers. There were two 50 km/h signs, one was positioned before the entrance to the east-to-north ramp, and one was located passed the entrance to the north-to-west ramp. Obviously, it is not clear at all whether these two signs are for the whole intersection including the loops, or only for the ramps, or for the straight sections.

Concerning site B, two different speed limits, that is, 30 and 50 km/h, were posted within the same interchange. Although it is beyond the scope of this paper to discuss this, it cannot be acceptable to post a 30 km/h limit on a major arterial (dual carriageway) without any prior (gradually decreasing) speed signage. One ramp had a 50 km/h limit while the rest of the ramps, and the loops, had no speed signs at site B.

To make the situation more peculiar, sites C and D had "Give Way" and "Stop" signs at the exits of some of the loops, the purpose of which is hard to guess. Loops 1 and 3 of site C had speed limit signs (50 km/h). Only loop 2 of site D had a speed sign (30 km/h) which followed gradually decreasing limits of 50 and 70 km/h signs before the loop. This good practice was not present in any of the loops of all four interchanges, implying yet

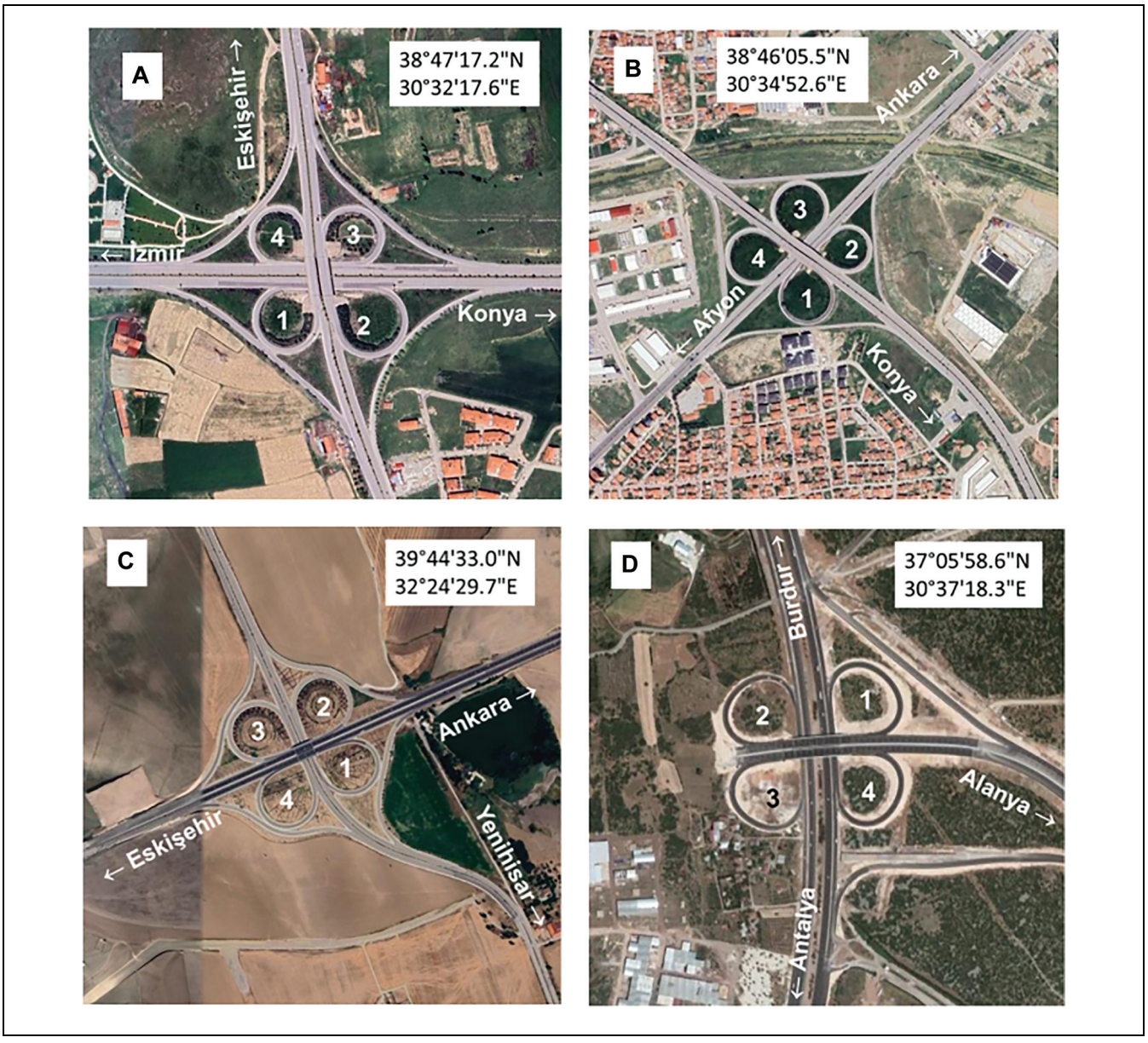


Figure 2. Data collection sites A, B, C, and D with central coordinates of each intersection.
Source: Google Maps.

another inconsistency. To sum up, out of these 12 loops of all sites, only three loops had their own speed limit signs, namely, loops 1 and 3 of site C, and loop 2 of site D. Table 1 summarizes this situation in a matrix format. Later in the paper (in the Speed Limit Implications section), further discussion will take place, together with the findings.

Data Collection Method

The test vehicle used in the study was a saloon car with a digital speedometer and a built-in navigation screen. Before the tests, the tires were checked by an expert garage to make sure that all four tires had equal pressures for the desired horizontality (Figure 4). Also, before each test, the vehicle was parked on a level surface in various directions to see if the ball-bank indicator shows 0° in every direction on the same spot when the vehicle was stationary. A tripod and a camera were positioned inside the car in the center just behind the front seats (Figure 4). This camera was able to concurrently capture the car's speedometer, the navigation screen (the car's real-time position on the map), the ball-bank device mounted on top of this screen, and the outside view from the

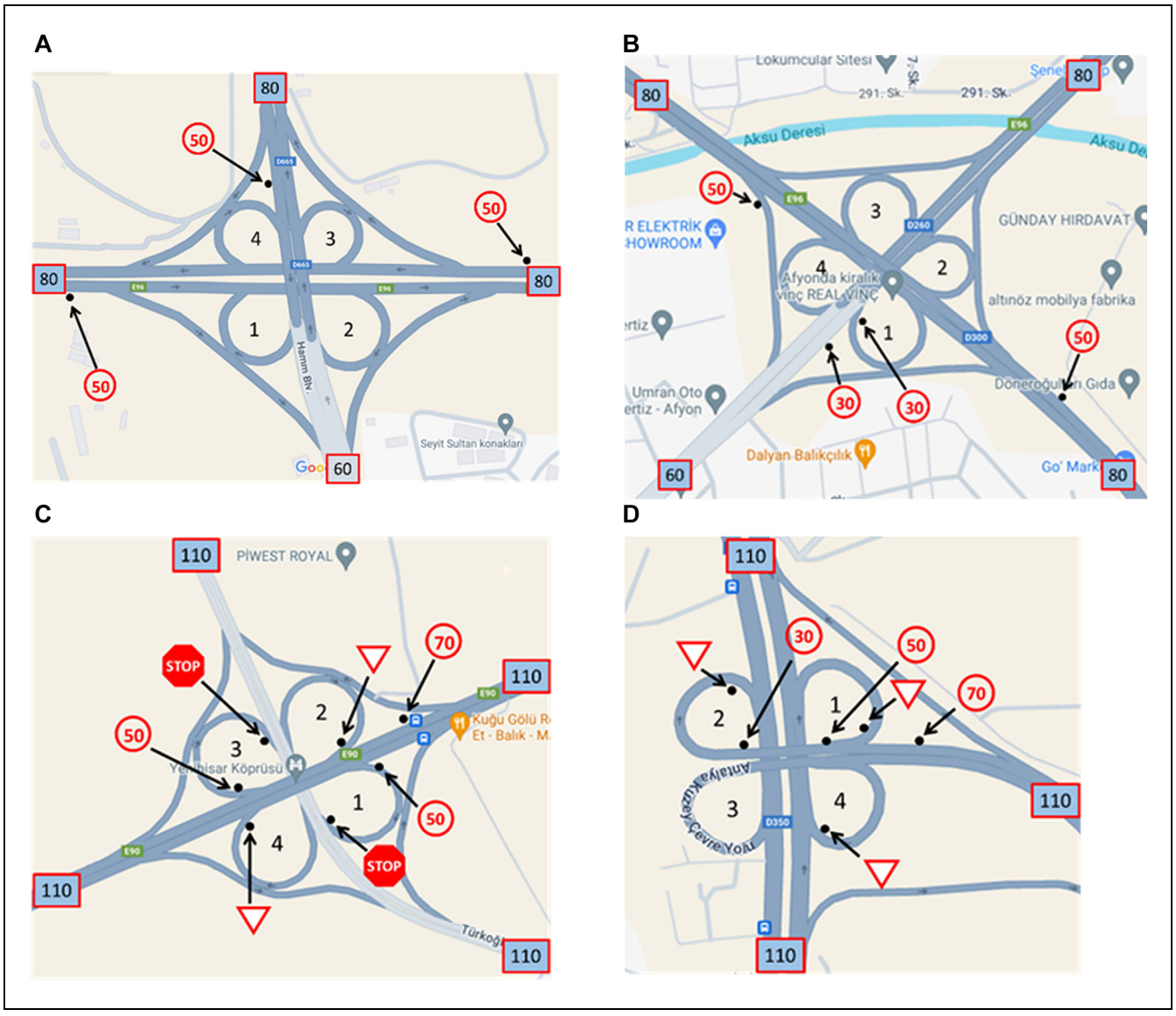


Figure 3. Improper loop signage which also lacks regularity (Sites, A, B, C and D).
Source: Base map from Google Maps.

windshield. In all test runs, the vehicle was driven by the researcher himself to maintain uniformity throughout the study.

After the tests, the video files were transferred to a computer for the analyses. The films were analyzed second-by-second by pausing the recording at the beginning of each second (using video player software). For instance, for a 1 min recording, 60 sets of readings were obtained, each set containing a real-time ball-bank reading and a corresponding speedometer (dashboard speed) value.

It should be remembered that, for better safety, car manufacturers configure vehicles' speedometers so that the displayed speeds are exaggerated by a small amount compared with true values. Since this conservative discrepancy might change from vehicle to vehicle, readers may want to compare the speed readings of the present paper with other research findings (that are possibly obtained by measuring speeds from outside their test vehicle), and will need to know how much deduction should be made for more universal comparisons. For this reason, before the actual data collection, a calibration study was conducted by the same test vehicle on an empty, flat and straight road of a university campus. The test vehicle was driven (in five runs) between two points, the coordinates of which are known, at constant speeds of 35, 40, 45, 50, and 55 km/h using the vehicle's cruise control. The distance between these two points (99.8 m) was measured by

Table 1. Loops Connecting Same/Different Facilities

Loop No.	Connects	National speed limits "from–to" (km/h)	Speed limit sign at interchange approach (km/h)	Speed limit sign at loop entrance (km/h)
Site A				
1	N to E	80–80	50	NA
2	W to N	80–80	50	NA
3	S to W	60–80	NA	NA
4	E to S	80–60	50	NA
Site B				
1	NW to NE	80–80	NA	NA
2	SW to NW	60–80	NA	NA
3	SE to SW	80–60	50	NA
4	NE to SE	80–80	NA	NA
Site C				
1	SW to NW	110–110	NA	50
2	SE to SW	110–110	NA	NA
3	NE to SE	110–110	70	50
4	NW to NE	110–110	NA	NA
Site D				
1	S to S	110–110	NA	NA
2	W to S	110–110	70	30
3	N to E	110–110	NA	NA
4	N to N	110–110	NA	NA

Note: E = east; N = north; S = south; W = west; NA = not available.



Figure 4. Preparation of the vehicle (at a garage, Afyon) (*left*) and configuration of in-vehicle equipment (*right*).

the Geomatics Department of that university. An in-vehicle video camera, viewing at a right angle from the direction of travel, recorded the vehicle's position using two reference points at the entry and exit of the test corridor. Then, in the office, by means of high precision video player software, the entry and exit times were obtained and the vehicle's actual speeds were calculated. The test was repeated twice to find an average value. As a result, it was found that the test vehicle's speedometer displays speeds about 2.2 km/h higher than the true values for the speed range in question (i.e., 35–55 km/h). The findings are summarized in Figure 5. The horizontal axis of the figure shows the test vehicle's automatic cruise control speed which is also the speedometer (dashboard) value.

Findings

Loop-by-Loop Ball-Bank Profiles

Firstly, the relationship between cruise speeds and the corresponding ball-bank readings are displayed in Figures 6 to 9. Four runs were conducted for each loop

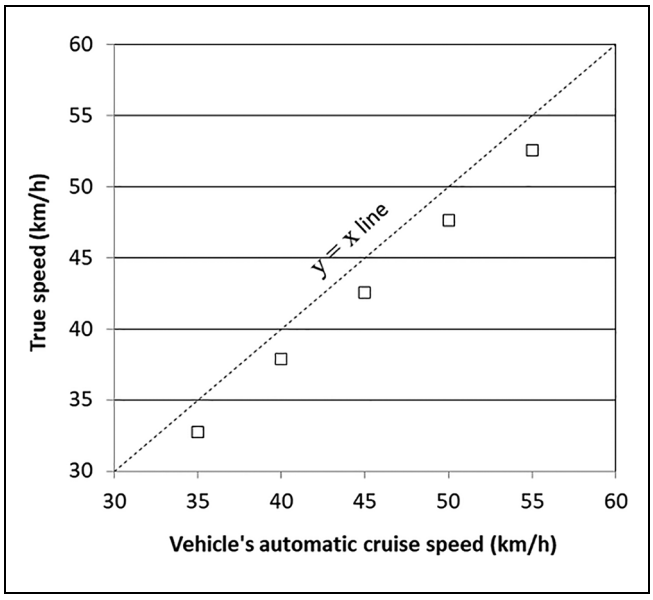


Figure 5. Discrepancy between the dashboard speeds and the true values.

of each interchange at various speeds. In these figures, while the primary vertical axis shows the ball-bank readings, the secondary (right) vertical axis is the corresponding instantaneous speed of the vehicle, read from the vehicle's speedometer. The *x*-axis shows the test duration in seconds. However, it should be noted that each visit of each loop is displayed in isolation in time. In other words, the durations of each run are discontinuous, as no ball-bank or speed data are shown between each run and between each loop. This is because the straight sections between the loops, which normally produce very low (or zero) ball-bank readings for every speed level, are not of interest.

During the actual (ball-bank) tests on each of the four sites, the vehicle was driven at constant speeds as much as possible using the vehicle's cruise control. Minor fluctuations in ball-bank readings (less than 2°) are largely because of the difficulty of steering the vehicle in completely smooth circular paths, as human hand or vehicle agitations do occur when driving. Therefore, making macroscopic observations and interpretations are more

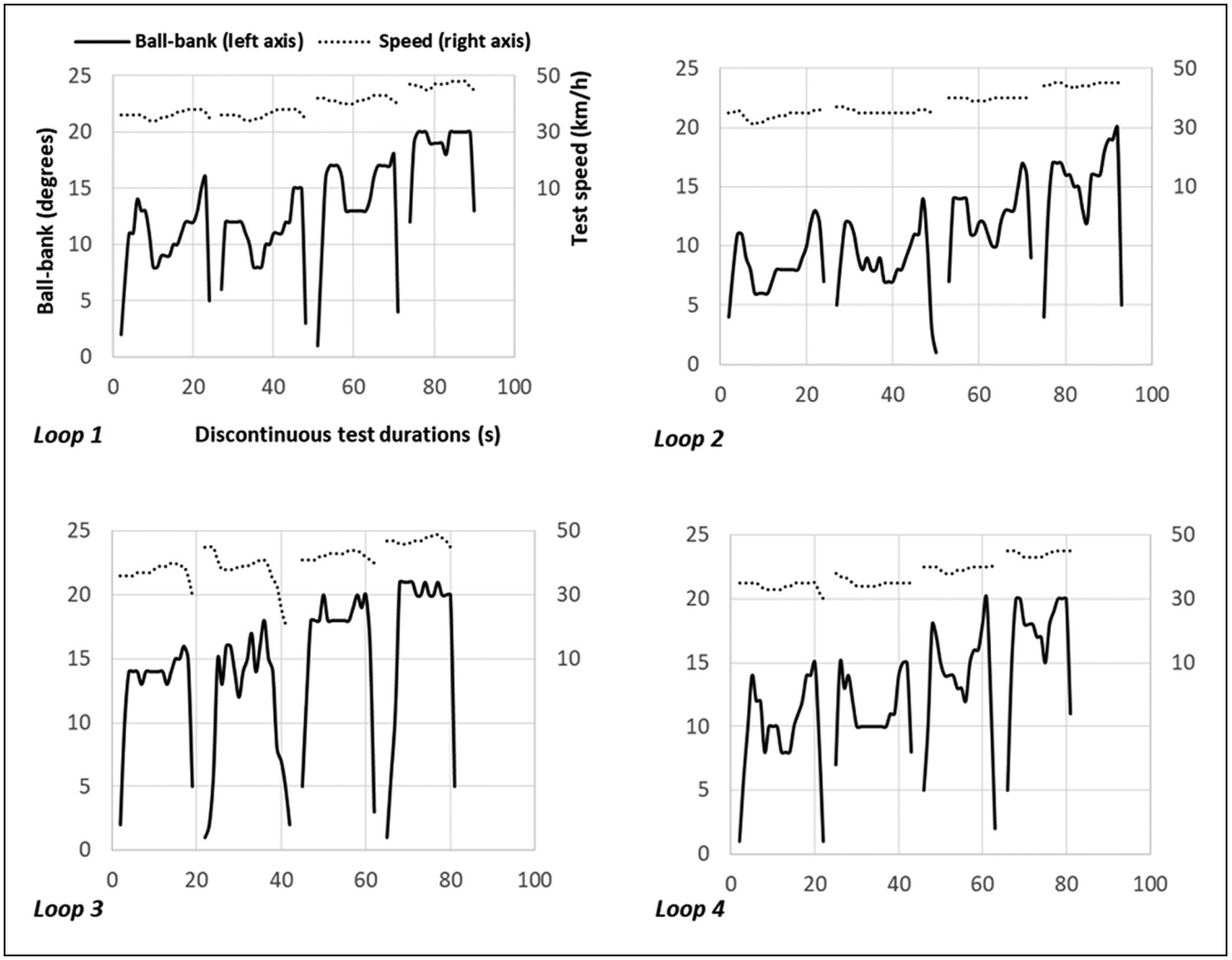


Figure 6. Ball-bank readings at various test speeds (intersection A).

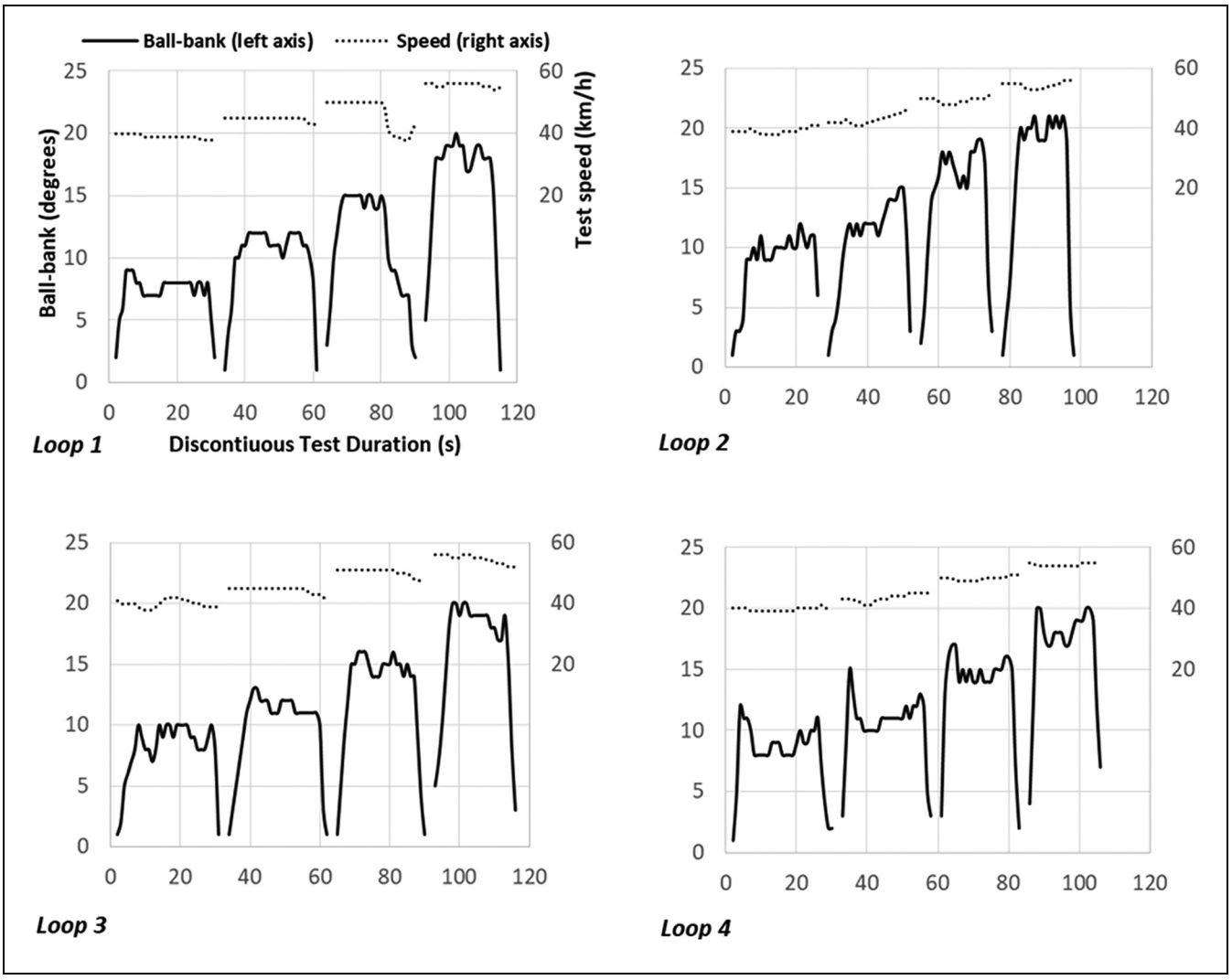


Figure 7. Ball-bank readings at various test speeds (intersection B).

appropriate than paying unnecessary attention to small fluctuations. Sudden speed drops, however, appearing in the second run of loop 3 of intersection A (Figure 6), in the third run of loop 1 of intersection B (Figure 7), and in the second runs of loops 2 and 3 of intersection D (Figure 9) were because of catching up with slow-moving vehicles traveling in front of the test vehicle.

In these figures, it is clearly visible that the ball-bank readings exhibit two peaks for some of the loops. There are two causes of this behavior. The first one is over-steering (not parallel to the loop curvature) at loop entrances and exits because of the non-existence of transition curves between the straight sections and the loops. The second cause is the noncircular loop geometry. Although the loops look like circles, especially for sites A, B and C (Figure 2), having carefully checked their geometric shapes, it was realized that some of the loops are made of compound curves. As an example, in Figure 10, while a circle can be drawn to follow the middle of the lane at loop entrance of site A, its radius falls short as the middle of the loop is reached. This results in a double peak pattern for this particular loop, as was observed in loop 2 of Figure 6. In the second depiction of Figure 10, the circle drawn fits perfectly for the entirety of the loop, passing through all along in the middle of the lane and producing a more uniform pattern (or at least no double peaks), as shown in loop 3 of Figure 8. The loops of intersection D, however, are more visibly in compound curve nature (Figure 2), producing much neater patterns of double peak fashion (Figure 9).

In the following sub-sections, three criteria will be introduced to be able to understand how the test vehicle negotiates the loops of these interchanges. These criteria will be 1) first maximums, 2) rate of change of radial acceleration, and 3) average riding comfort along a loop.

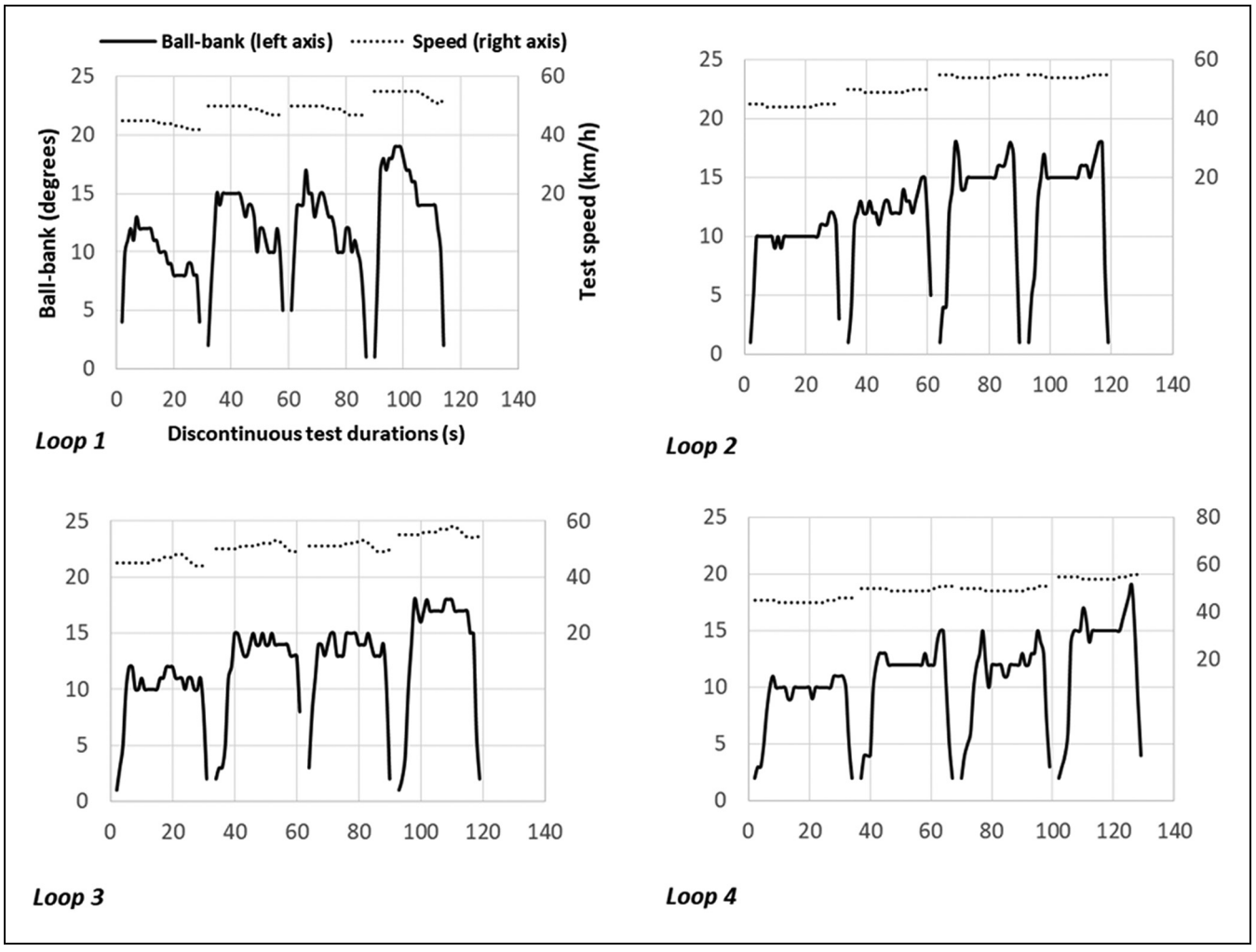


Figure 8. Ball-bank readings at various test speeds (intersection C).

First Maximums. It is very important that, when drivers face a cloverleaf interchange, as they exit the tangent section of the highway toward a loop, they reduce their speed to a safe level to be able to negotiate the loop they are about to take. Drivers may sometimes experience a surprise lateral acceleration, possibly because of inconsistency among the loops of the same intersection or among various intersections. In the absence of mandatory or advisory speed signs, making a mistake at this moment may be critical. Therefore, in the following, we will focus on the first maximum ball-bank reading for each loop against its corresponding speed. Figure 11 displays this relationship for all sites.

Four data points for each loop are shown on each diagram in association with the four runs from their corresponding figures (Figures 6 to 9). In total, 16 data points are displayed for each intersection. In other words, each data point in Figure 11 is the first highest ball-bank reading of each run of each loop. For example, let us consider the first run of loop 1 of intersection A (Figure 6). The first highest ball-bank reading is 14° against a speed of 36 km/h. This pair is shown in Figure 11 as the first data point. The rest of the data points in Figure 11 are obtained in the same way.

Linear regression lines are fitted on these data points to show the overall behavior of the plots with increasing speed values. No further statistical importance needs to be attached to these lines. To be able to compare all four sites easily on the same figure, both horizontal and vertical axes in all four diagrams had identical value ranges.

As an example discussion, the following deductions can be made for intersection A (the top left diagram of Figure 11). Loop 4 exhibits the highest ball-bank values for the corresponding speeds. A ball-bank range of 14°–16°, a reasonable comfort limit for the same speed band, recommended by the majority of the literature (Figure 1), is produced at around 35–38 km/h of speeds in loop 4. The same ball-bank values are achieved at about 40–43 km/h in

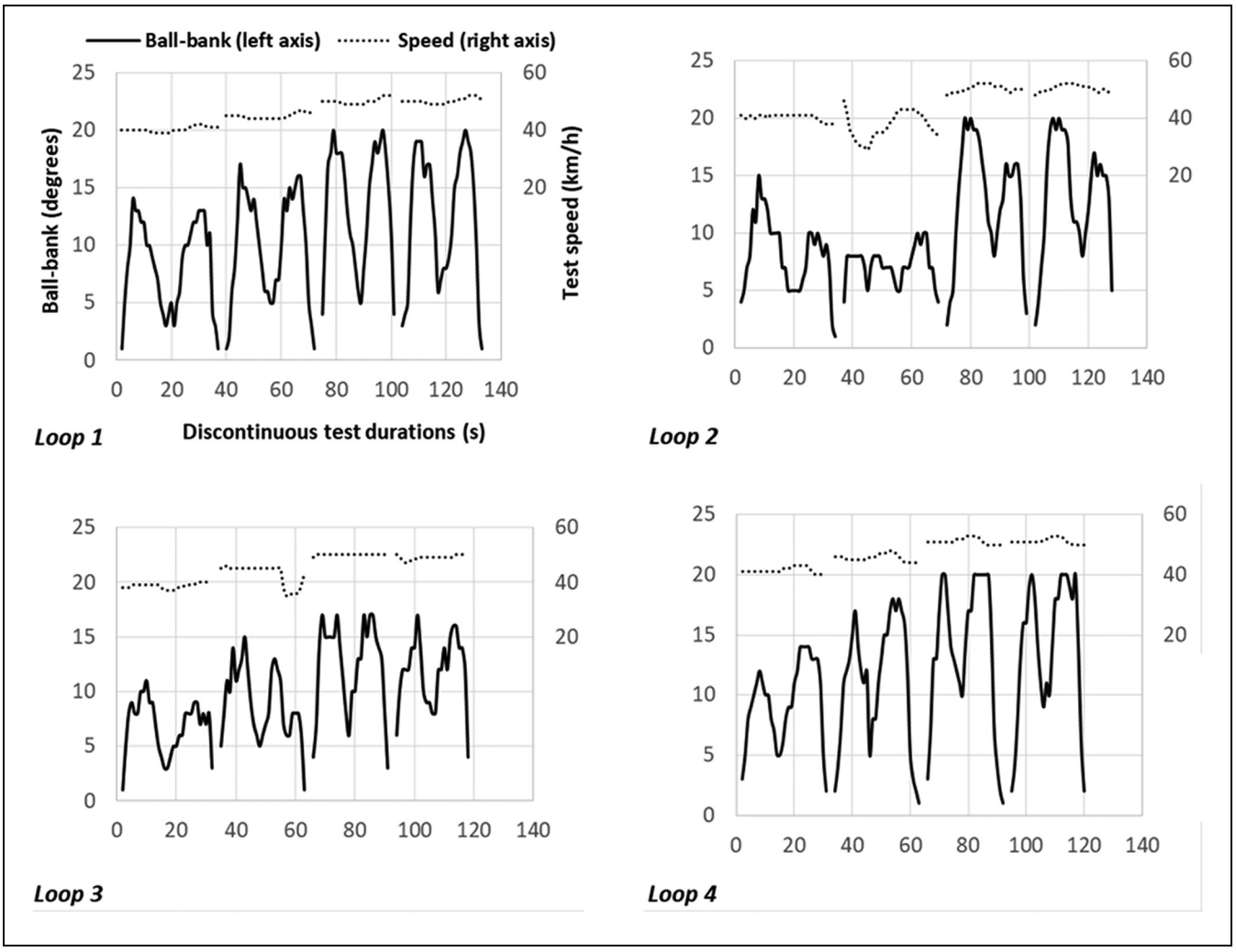


Figure 9. Ball-bank readings at various test speeds (intersection D).

loop 2 referring to about 5 km/h speed difference between the two loops of the same cloverleaf intersection. Also, the regression line representing the data points of loop 2 is noticeably lower than the rest of the three lines.

Table 2 compares all loops of all sites in this respect for two example limits of ball-bank indication (i.e., 16° and 20°). It is evident from the table that a driver who wishes not to exceed, say, 16° of ball-bank as their comfort limit, has to negotiate loop 4 of intersection A at 38 km/h, while the same driver can enter loop 2 of intersection C at 53.2 km/h with the same lateral discomfort. Obviously, this driver will experience about 15.2 km/h speed difference between these two intersections. Concerning the 20° of a very high level of ball-bank value (as perhaps an absolute limit), this gap is about 14.9 km/h between loop 4 of intersection A and loop 3 of intersection C. As was also mentioned above in the Data Collection section (after Figure 2), ramps and loops connect two links with different speed limits. Therefore, correct choice of design elements, together with correctly chosen speed limit signs (mandatory or advisory), play a very important role in highway design, a feature which is not practiced in Turkey, where a single design speed is used regardless of the general speed limits of the facilities they connect (*41*).

The findings of Figure 11 may also be interpreted the opposite way. For example, if a driver always prefers to enter the loops of such interchanges at, say, 45 km/h, as their custom speed or anticipated safe speed limit, they will experience quite varying lateral acceleration levels when taking the loops of these intersections. That is to say, they will experience only 9.7° of ball-bank angle when entering loop 2 of intersection C, and 20.3° when entering loop 3 of intersection A at the same speeds, implying a huge difference in comfort (and perhaps in safety), even within the same country. Readers may extend this interpretation for various other speed levels by means of the regression equations of Figure 11.

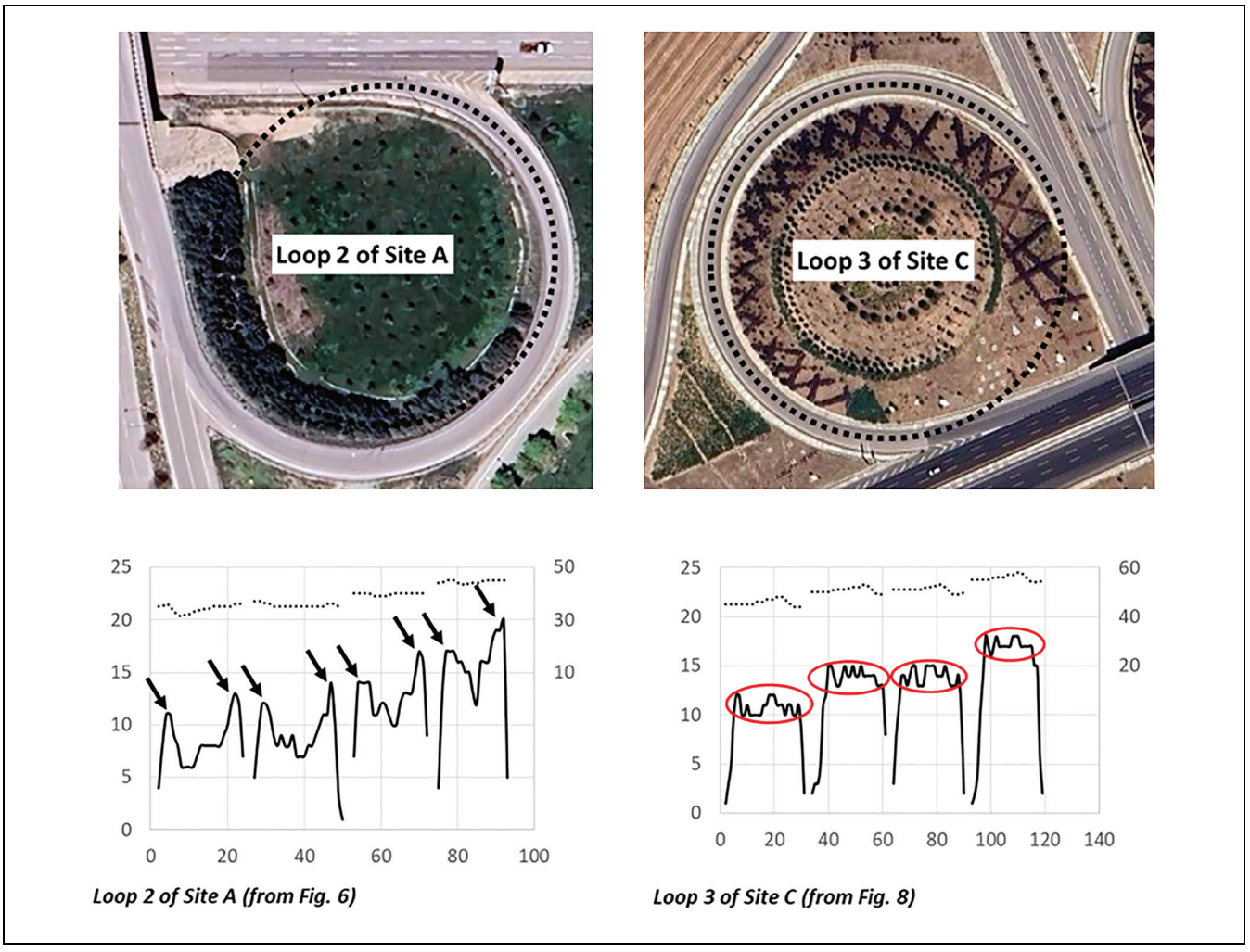
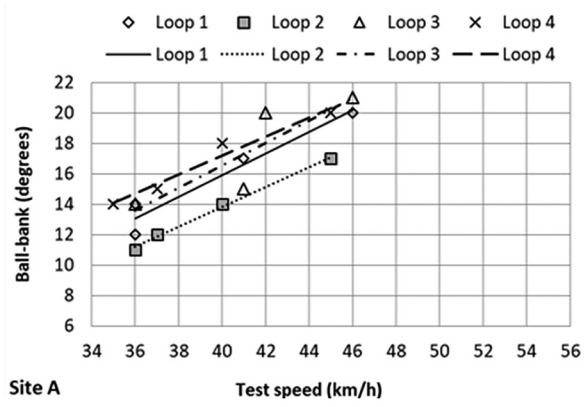


Figure 10. Examples of non-circular and circular loop geometries (note the two circles drawn with broken lines in black).

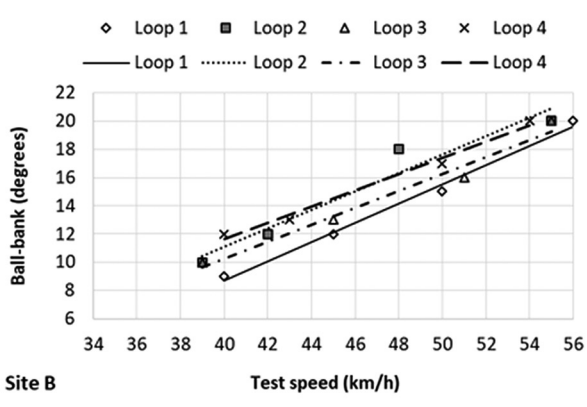
The Rate of Change of Radial Acceleration (Jerk). When a vehicle enters a loop, it undergoes a change of radial acceleration from nought to a certain value, because of a change of curvature (from infinite radius at tangent to the radius of the loop). The opposite is true when exiting a loop. With point mass assumption, the centripetal acceleration, perpendicular to the instantaneous velocity, is directed toward the centre of the horizontal curve given by v^2/R, where v is speed of vehicle (m/s) and R is the radius (m). According to Newton's second law, the net radial force (in kgm/s^2) exerted on a particle of mass m (kg) is $\frac{mv^2}{R}$. On a superelevated curve, a portion of lateral acceleration is offset by the banking of the curve, such that $\frac{e}{100} + f = \frac{V^2}{127R}$, where f is side friction factor, e is superelevation (in %), and V is speed of the vehicle in km/h (the gravitational pull, g, is taken as 9.81 m/s^2).

As Carlson and Mason point out, while the left-hand side of this equation is the amount of lateral acceleration supplied, the right-hand side represents the demanded lateral acceleration (*20*). If the body-roll angle is ignored, the ball-bank reading equals the combined effect of the lateral acceleration angle and the superelevation angle (arctan e). The ball-bank indicator reading itself, therefore, could be a measure of radial acceleration (*20*). The ratio of $\frac{v^2}{gR}$ (or $\frac{V^2}{127R}$) is called the "centrifugal ratio" and the rate at which this ratio changes has been used by engineers as a measure of comfort for both highways and railways.

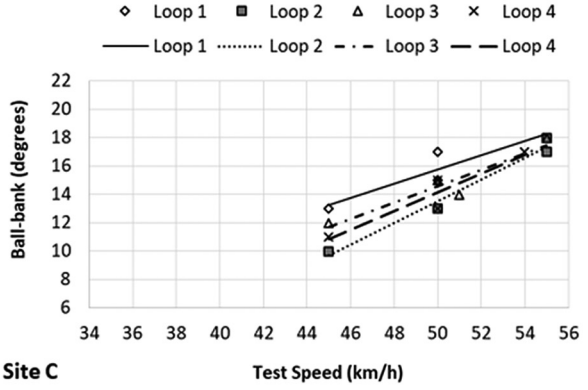
In design, it is desired that the rate of change of radial acceleration should not exceed certain levels. A suitable length of a transition curve, for example, is determined by limiting the change of this ratio in horizontal curve design (*42*). O'Flaherty stated that motorists feel uncomfortable and the vehicle becomes harder to hold on the road when the change of this ratio exceeds about 0.3 m/s^3 (*43*). In the very early years of research, this value was selected as low as 0.25 m/s^3 (*44*). Schofield and Breach gave more acceptable values as 0.3 m/s^3, 0.45 m/s^3 and



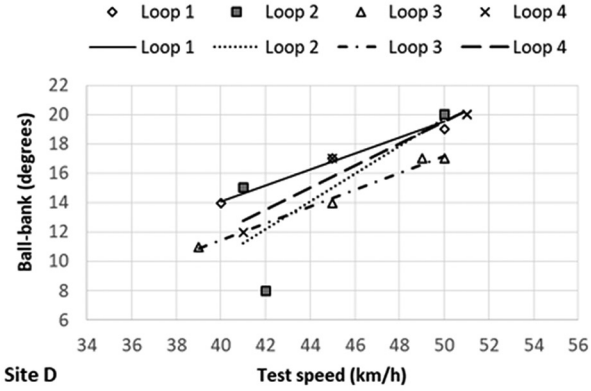
Loop	Regression equation	R^2
1	y = 0.709x - 12.436	0.94
2	y = 0.653x - 12.296	1.0
3	y = 0.739x - 12.98	0.75
4	y = 0.621x - 7.63	0.96



Loop	Regression equation	R^2
1	y = 0.682x - 18.568	0.99
2	y = 0.653x - 15.053	0.94
3	y = 0.602x - 13.847	0.97
4	y = 0.574x - 11.35	0.99



Loop	Regression equation	R^2
1	y = 0.5x - 9.25	0.85
2	y = 0.764x - 24.636	0.98
3	y = 0.576x - 14.212	0.90
4	y = 0.663x - 18.963	0.90



Loop	Regression equation	R^2
1	y = 0.546x - 7.7273	0.97
2	y = 0.945x - 27.485	0.67
3	y = 0.572x - 11.415	0.99
4	y = 0.75x - 18	0.95

Figure 11. First maximum ball-bank points (all four sites).

$0.6\,m/s^3$, although the American Association of State Highway and Transportation Officials states that it could be as high as $0.9\,m/s^3$ in highway design (*45*, *46*). To suggest a suitable numeric value is beyond the scope of the present paper, however, we will demonstrate the (in)consistency of the rate of change of radial acceleration among the loops of the interchanges studied. Refer to Kilinc and Baybura for a more detailed review of past research on possible numeric values of jerk (*47*).

The previous section of this paper studied the first maximum ball-bank readings for each loop. In association with that approach, in this section, we will focus on how quickly a certain level of ball-bank angle is reached, as the test vehicle enters a loop of a cloverleaf intersection, and diminishes as the vehicle leaves the loop. An add-in feature of a video player software was used for this purpose for more precise frame captures (Figure 12).

Table 2. Certain Levels of Ball-Bank Reached at Various Speeds

Loop No.	Speed at which 16° of ball-bank is reached	Biggest difference among loops	Biggest difference among sites	Speed at which 20° of ball-bank is reached	Biggest difference among loops	Biggest difference among sites
Site A						
1	40.1 km/h			45.7 km/h		
2	43.3 km/h	5.3 km/h		49.5 km/h*	5.0 km/h	
3	39.2 km/h			44.6 km/h		
4	38.0 km/h			44.5 km/h		
Site B						
1	50.7 km/h			56.5 km/h		
2	47.5 km/h	3.2 km/h		53.7 km/h	2.8 km/h	
3	49.6 km/h			56.2 km/h		
4	47.6 km/h			54.6 km/h		
Site C			15.2 km/h			14.9 km/h
1	50.5 km/h			58.5 km/h*		
2	53.2 km/h	2.7 km/h		58.5 km/h*	0.9 km/h	
3	52.4 km/h			59.4 km/h*		
4	52.8 km/h			58.8 km/h*		
Site D						
1	43.5 km/h			50.8 km/h		
2	46.0 km/h	4.4 km/h		50.2 km/h	5.7 km/h	
3	47.9 km/h			54.9 km/h*		
4	45.3 km/h			50.7 km/h		

*projection.



Figure 12. Millisecond precision of a video player software (shown at the top right corner).

As soon as the vehicle passes the zero ball-bank reading when rotating clockwise at the approach of a loop, the ball-bank versus the corresponding speed values were recorded for every 0.5 s increment. Figure 13 summarizes the findings for all sites. It should be remembered that the ball-bank readings here are the combined values of lateral acceleration including the superelevation element (if present).

To be able to rightfully compare all four sites, similar speed groups were targeted (i.e., circa 50 km/h as a common speed group) for each intersection. The speed values were slightly lower at site A than the rest, as it was unsafe to enter the loops of intersection A at higher speeds. The speed values shown in the legends of Figure 13 are averages of six readings (over 2.5 s). Ideally, for consistency reasons, the curves should not differ much within the same interchange, or even within the same jurisdiction. However, loop 1 of site A exhibits a higher pattern than the rest of the loops of the same intersection. Likewise, loop 3 of site D also gave a higher ball-bank development over the first 2.5 s. While loop 2 of site B gave a mild growth of ball-bank angles over whole duration, the rest of the loops produced much quicker changes. Especially, loop 4 of site B reached 12° at the end of the 2nd second.

It should be noted that these results represent the entrance area to the loops, not the overall loop performance. For example, while loop 2 of site B has a smaller radius than the rest of the loops of the same interchange, and produced higher ball-bank readings on overall average (as will be shown later in the Average Riding Comfort along a Loop section), as far as entering to the loop is concerned, it gave a pleasing result in Figure 13. The need for some sort of easement curves to be used at loop entrances may gain importance here, but, again, this discussion is beyond the scope of the paper and left for further research. The slope of each curve in Figure 13 is the rate of change of lateral acceleration (combined with superelevation element, which was not directly and separately measured in the study). Table 3 summarizes

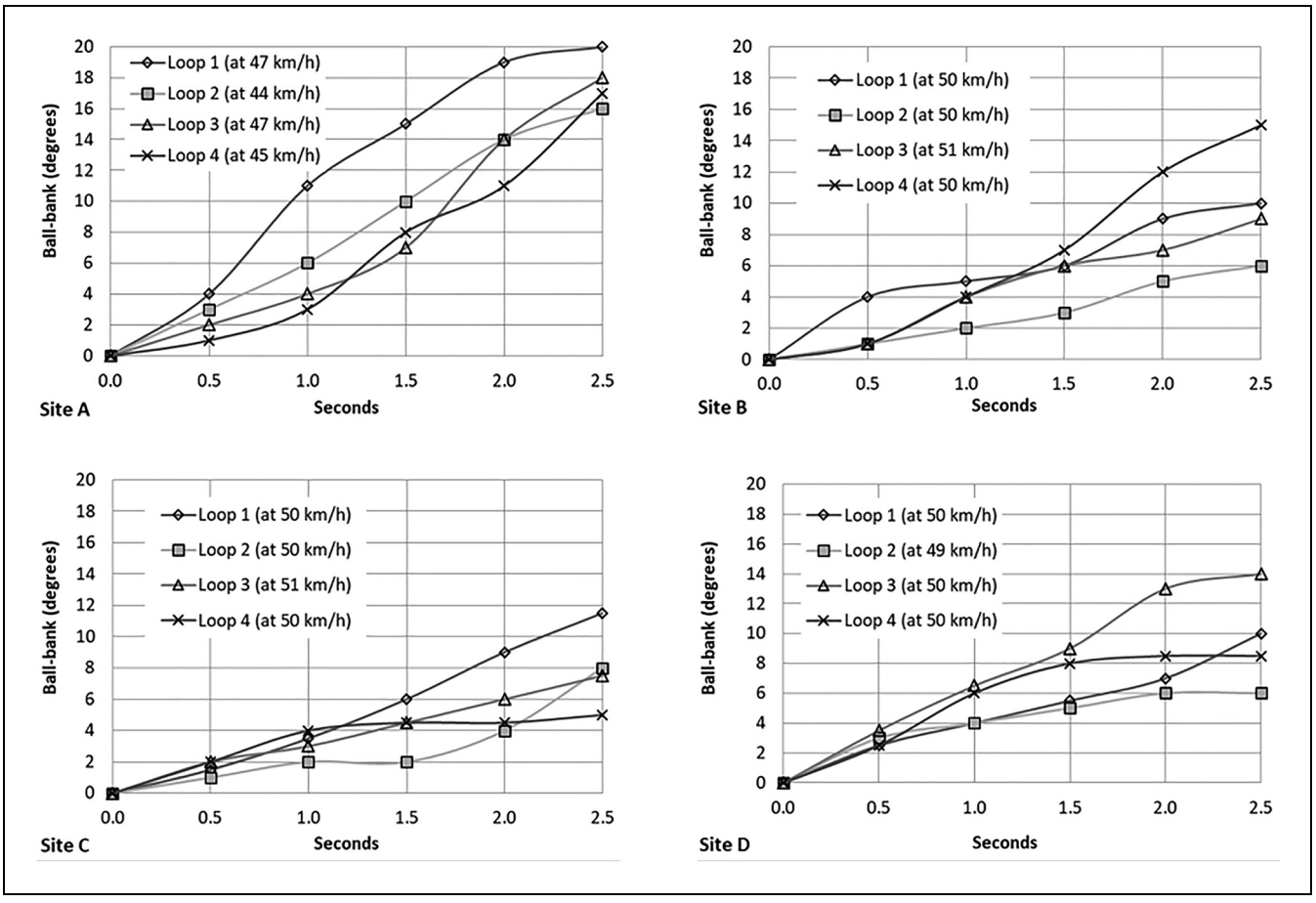


Figure 13. Development of lateral acceleration in detail at loop entrances.

Table 3. The Rate of Change of (Combined) Radial Acceleration (per Second)

Loop No.	During 1st second	During 2nd second	Biggest difference among loops	Biggest difference among sites
Site A				
1	0.194	0.141		
2	0.105	0.141	0.142	
3	0.070	0.176		
4	0.052	0.141		
Site B				
1	0.088	0.070		
2	0.035	0.052	0.106	
3	0.070	0.052		
4	0.070	0.141		
Site C				0.158
1	0.070	0.088		
2	0.035	0.035	0.07	
3	0.052	0.052		
4	0.070	0.018		
Site D				
1	0.070	0.052		
2	0.070	0.035	0.088	
3	0.123	0.105		
4	0.105	0.052		

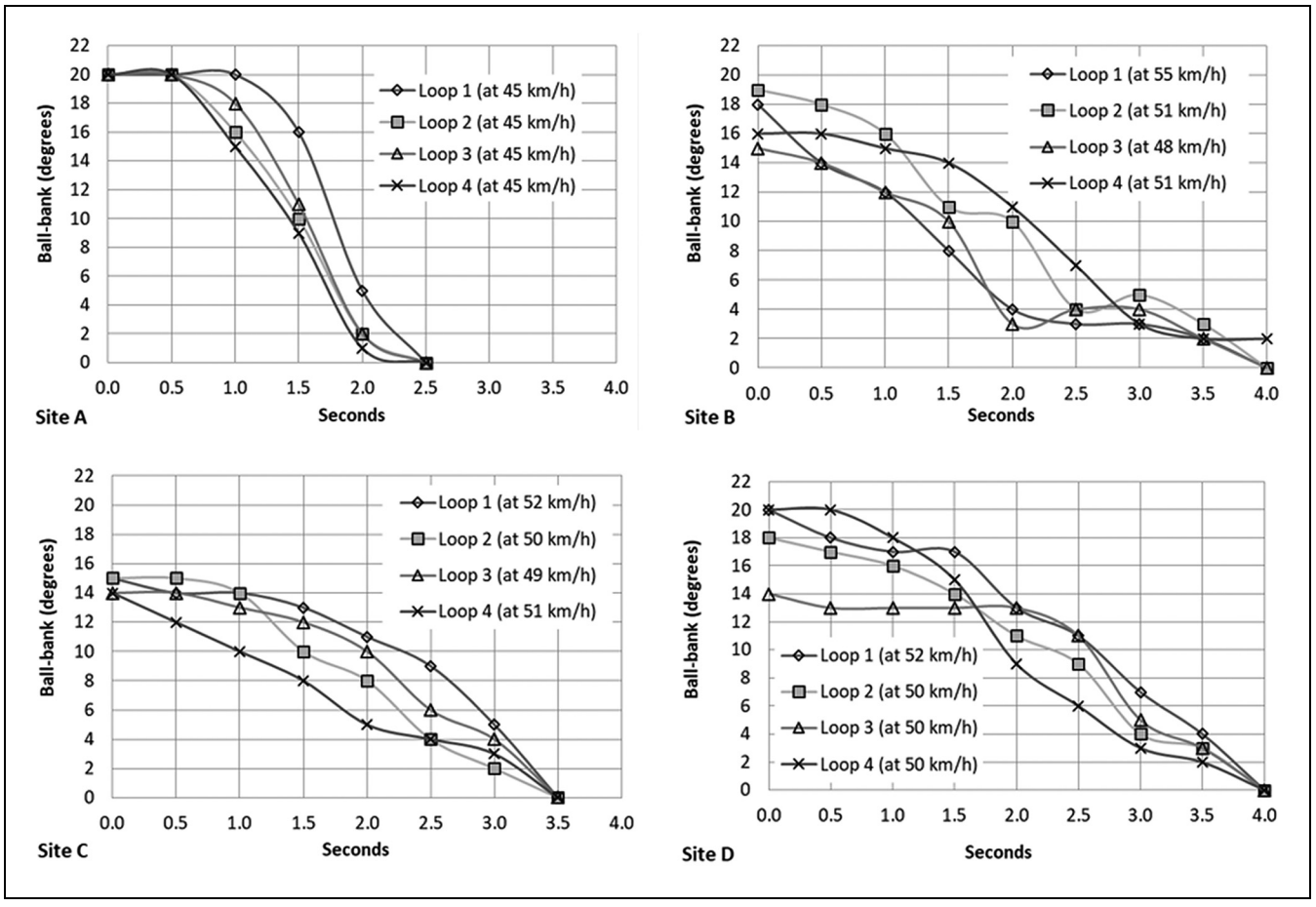


Figure 14. Diminishment of lateral acceleration in detail at loop exits (with prolonged horizontal axis for clarity).

these ratios for the first 2 s period. On studying this table, it can be seen clearly that the loops of some intersections are less consistent (such as site A) than others.

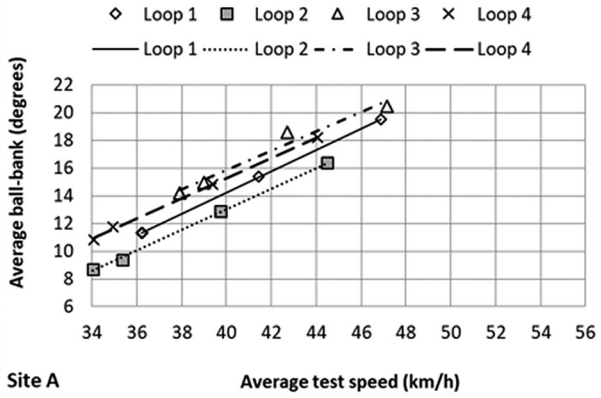
As far as the loop exits are concerned, similar analysis was conducted to reveal how fast the test vehicle corrects the steering wheel as it leaves the loop and joins the straight section of the main road (Figure 14).

All loops of site A exhibited a very quick drop of radial acceleration from about 20° to 0° in less than 2.5 s, while the rest of the sites completed this diminishment in about 4 s. Also, the lateral acceleration in loop 1 of site A lessened quicker than it did in the rest of the loops. Similar to Figure 13, the speeds shown in the legends of Figure 14 are average values taken over 4 s (nine readings). Since loop entrances are more critical (i.e., the change of radial acceleration takes longer at loop exits compared with loop entrances), no further discussion is thought to be necessary here.

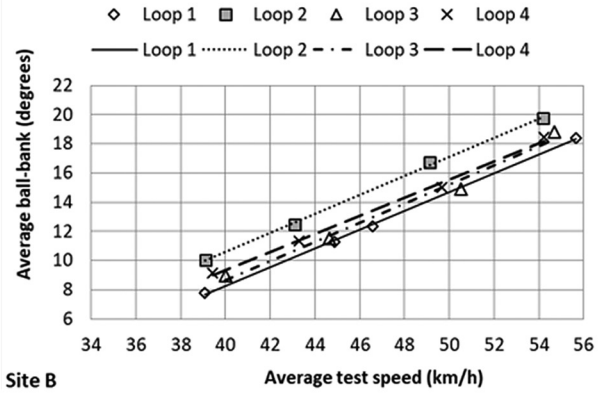
Average Riding Comfort along a Loop. The above two sets of analyses (i.e., the first maximums and the rate of change of radial accelerations at loop entrances) reflected the initial shocks faced by drivers when entering a loop. As another scrutiny, Figure 15 compares the average values (rather than a single maximum value) of all ball-bank readings between the first maximum reading and the last highest value of each loop. Each data point in Figure 15 represents the average value of a series of speed and ball-bank readings along the loop.

Loop 2 of intersection B differed from the other three loops of the same intersection (top right diagram of Figure 15) as it has higher ball-bank readings for all speeds. This is probably caused by inappropriate superelevation (as a design or construction mistake) for loop 2, which has smaller radius (as can be seen from Figure 2). Regression properties of these data points are summarized below each graph.

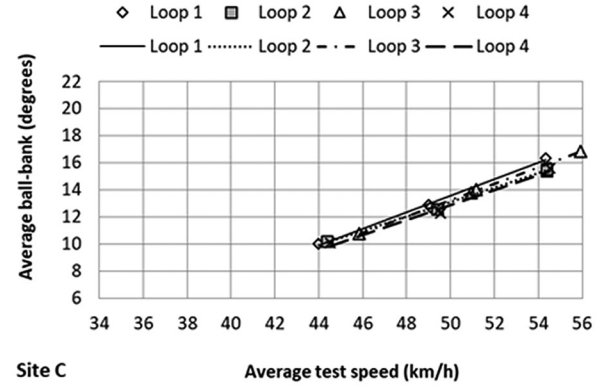
A similar table to Table 2 is provided here (Table 4) based on Figure 15. It is again very clear that, as an extreme example, a driver will experience, say, 16° of lateral discomfort (on average) along loop 3 of intersection A at a speed of 40.2 km/h, and the same amount of ball-bank angle is experienced at a speed of 55.7 km/h on average along loop 4 of intersection C. This 15.5 km/h difference among intersections, again, may have consistency



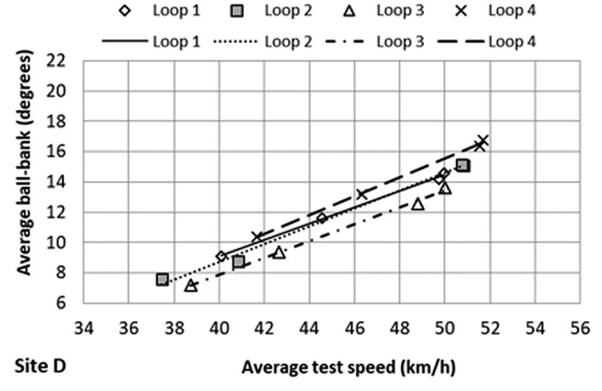
Loop	Regression equation	R^2
1	y = 0.769x - 16.516	1
2	y = 0.747x - 16.828	1
3	y = 0.701x - 12.179	0.97
4	y = 0.727x - 13.797	1



Loop	Regression equation	R^2
1	y = 0.643x - 17.49	1
2	y = 0.651x - 15.465	1
3	y = 0.656x - 17.606	0.99
4	y = 0.621x - 15.475	1



Loop	Regression equation	R^2
1	y = 0.610x - 16.962	1
2	y = 0.531x - 13.465	1
3	y = 0.606x - 17.03	1
4	y = 0.550x - 14.634	0.99



Loop	Regression equation	R^2
1	y = 0.541x - 12.558	1
2	y = 0.588x - 14.784	0.99
3	y = 0.555x - 14.331	1
4	y = 0.624x - 15.646	1

Figure 15. Average speed versus average ball-bank values.

issues. Based on these findings it can safely be stated that all four loops of intersection C have the best consistency figures compared with the other three intersections.

Speed Limit Implications

Figure 3 had shown that only three loops were equipped with their own speed limit signs (i.e., loops 1 and 3 of site C and loop 2 of site D), positioned at the entrances of these loops. The remaining 13 loops had no speed limit signs of any kind. The figure also showed that some of the approach links had speed limit signs. It may be assumed that these (more general) speed limit signs at approach links may well be interpreted by drivers as governing speed limits also for the loops that are entered from those links (with speed limit signs). Table 5 is

Table 4. Certain Levels of Ball-Bank Reached at Various Speeds

Loop no.	Speed at which 12° of ball-bank is reached	Biggest difference among loops	Biggest difference among sites	Speed at which 16° of ball-bank is reached	Biggest difference among loops	Biggest difference among sites
Site A						
1	37.1 km/h			42.3 km/h		
2	38.6 km/h	4.1 km/h		44.0 km/h	3.8 km/h	
3	34.5 km/h *			40.2 km/h		
4	35.5 km/h			41.0 km/h		
Site B						
1	45.8 km/h			52.1 km/h		
2	42.2 km/h	3.6 km/h		48.3 km/h	3.8 km/h	
3	45.1 km/h			51.2 km/h		
4	44.3 km/h			50.7 km/h		
Site C			13.9 km/h			15.5 km/h
1	47.5 km/h			54.0 km/h		
2	47.9 km/h	0.9 km/h		55.5 km/h	1.7 km/h	
3	47.9 km/h			54.5 km/h		
4	48.4 km/h			55.7 km/h		
Site D						
1	45.4 km/h			52.8 km/h*		
2	45.6 km/h	3.1 km/h		52.4 km/h*	3.9 km/h	
3	47.4 km/h			54.6 km/h*		
4	44.3 km/h			50.7 km/h		

*projection.

Table 5. Ball Bank Degrees Would Be Produced, if Speed Limits "in the Vicinity" Were to Be Complied

Loop No.	National speed limits "from–to" (km/h)	Speed limit sign at interchange approach	Speed limit sign at loop entrance	If entered at (km/h)	Ball-bank produced according to the criterion of	
					First maximum	Average riding comfort
Site A						
1	80–80	50 km/h	NA	50	23.0°*	22.0°*
2	80–80	50 km/h	NA	50	20.1°*	20.5°*
3	60–80	NA	NA	60	SORI	
4	80–60	50 km/h	NA	50	23.4°*	22.6°*
Site B						
1	80–80	NA	NA	80	SORI	
2	60–80	NA	NA	60	24.2°*	23.6°*
3	80–60	50 km/h	NA	50	16.3°	15.2°
4	80–80	NA	NA	80	SORI	
Site C						
1	110–110	NA	50 km/h	50	15.8°	13.6°
2	110–110	NA	NA	110	SORI	
3	110–110	70 km/h	50 km/h	50	14.6°	13.3°
4	110–110	NA	NA	110	SORI	
Site D						
1	110–110	NA	NA	110	SORI	
2	110–110	70 km/h	30 km/h	30	0.9°*	4.5°*
3	110–110	NA	NA	110	SORI	
4	110–110	NA	NA	110	SORI	

Note: SORI = sliding or rollover is inevitable (i.e., the projected ball-bank angle is above 25°); NA = not available. The table should also be studied in association with Tables 2 to 4.
*projection.

arranged to show the corresponding ball-bank angles (observed or projected) if vehicles were to enter these loops at the speed values shown in column 6 of Table 5 (with the column heading "If entered at (km/h)"). This column displays the minimum of the three speed values given in columns 3, 4, and 5. The ball-bank angles in columns 7 and 8 are computed using the regression equations of Figures 11 and 15. If the ball-bank agles computed exceed 25°, it was assumed that the vehicle is in danger of sliding or rollover—sliding or rollover is inevitable. Readers may compute corresponding ball-bank angles for various other speed values using those regression equations.

It is clear from the table that, at site A, if drivers approaching from the east assume that the only speed limit sign on the road is also valid for loop 4, then the lateral acceleration they will experience (23° and 22°, respectively) will exceed acceptable limits. Similarly, drivers approaching from the north, with the same assumption, will experience alike high values of lateral acceleration for both criteria. For site B, however, the same scenario produces only around 15°–16° ball bank angles for both criteria. Although the two loops of site A are consistent and the ball-bank values are within reasonable limits, the very low ball-bank readings of site D (0.9° and 4.5°) imply that the current speed limit would be very conservative as far as lateral accelerations are concerned.

Concluding Remarks

Interchange loops, especially with small radii, are potential risk areas as far as sliding and rollover type accidents are concerned when negotiating these curves. Adequate speed signs are key for proper highway operation. In the absence of such signage, however, inaccurately chosen speeds by drivers may result in serious consequences, especially since radius and superelevation balances are inconsistent from loop to loop or from interchange to interchange within the same country. To be able to test the extent of this problem, using the concept of radial acceleration is a good approach. Although ball-bank indicators are widely used in several countries around the world, their use is not a requirement in many other places, including Turkey, in setting or assessing curve advisory speeds. However, many high-type roads in Turkey, including interchange ramps and loops, lack speed limit signs and are subject to serious safety risks. This paper, therefore, draws the attention of authorities with similar ill-practice to the problem by showing how a test vehicle negotiates the loops of such major interchanges by means of a cost-effective way of obtaining "basic" sets of data. The paper introduced three testing criteria as 1) first maximum, 2) rate of change of radial acceleration, and 3) average riding comfort. The findings underline the importance of consistent and proper use of speed limit signs for such critical elements of highway networks. Although within the same country, around 10° variation of ball-bank indications for the same speed level, or about 15 km/h speed variations for the same ball-bank degree, among the interchanges studied in the paper, highlight the potential risks of such places where drivers are left with "unaided" speed decisions. This paper also revealed that the change of radial acceleration varied by about 0.14°/s among the loops of the same interchange and by about 0.16°/s among the interchanges studied. As a result, since it is very costly to make physical changes to these loops to increase radii or superelevation rates, additional and more appropriate speed limit signage before the loops will definitely improve the situation as a practical remedy in the short term. Using the regression lines or the associated tables produced in this paper, local authorities will be able to make improvements in suitable advisory speed limits for these interchanges.

The speedometer calibration work, conducted before the actual data collection, found that the test vehicle's dashboard speeds are about 2 km/h higher than the true values for a particular range of 35–55 km/h test speeds. This will help other researchers compare the present findings with other studies using different speed data collection techniques.

A possible limitation of the study is that the number of runs for each loop was only four, because of the time-consuming data extraction procedure of the mechanical ball-bank methodology. Further work may be carried out for the same research objectives at similar interchanges using a digital ball-bank device. However, this will require a new technique of simultaneously capturing the ball-bank readings and the corresponding dashboard speed values, as in-vehicle video recording will have difficulty in viewing the screen of the digital ball-bank device. This remains an interesting challenge for researchers who want to adhere to basic approaches to eliminate the synchronisation of more sophisticated methods, such as integrated GPS devices.

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.

Declaration of Conflicting Interests

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