Use of GPS data logger and ball bank indicator for detection of potentially hazardous locations on roads

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Abstract

This paper deals with a detection of potential hazardous locations on roads. The geometric characteristics of road (horizontal alignment, vertical alignment and superelevation) play a significant role on driving safety. Last decades many researchers analyzed highway design consistency in terms of maintaining the desired travel speed. They proposed the use of operating speed models for checking road design consistency from safety point of view. Many of them suggested a quantitative approach to evaluate design consistency based on vehicle stability, proposing different superelevation and side friction distribution.

This paper presents a method for determining the road alignment characteristics which can significantly affect driving safety (superelevation changes, side friction demand, radii....). The proposed method involves a device called “ball bank indicator” and specialized GPS device. The most significant impact on driving safety in curves has side friction demand which depends on vehicle speed, vehicle and tire characteristics and superelevation rate.

We equipped test vehicle with PerformanceBox, 10 hz GPS data logger based on the Racelogic VBOX which is used by the majority of car and tire manufactures around the world to assess car and tire performance. PerformanceBox is a GPS based performance meter for measuring side (radial) forces, speed, braking distance and many more. Performance tool software allows graphical analysis of acceleration (lateral and longitudinal), braking and cornering characteristics. The highway location can easily be export to Google earth, Track vision and other mapping software at various coordinate systems.

In addition to this device it was used a “ball bank indicator”, an inclinometer which measures influence of centripetal acceleration, body roll and cross slope.

These devices were used to get a continuous data of side friction demand on five km long segment of motorway A1 Zagreb-Split on which many accidents occurred during last decade. Two locations with large change of radial acceleration (several times larger than allowed) were identified in test drives. Great demand for side friction or acceleration change can lead to inadequate driver’s reaction (sudden speed change or a sudden maneuver) which can result with overcoming side friction supply, or loss of vehicle stability and an accident.

Key words: Road safety, radial acceleration, radial acceleration change, ball bank indicator

1 Introduction

Accidents on the roads happen every day. However, on some locations the accidents occur more often. Thus, on the motorway A1 Zagreb-Split, 388 km long, the largest number of
accidents occurs on the section between 339 and 341 km, near the service area Sitno (Figure 1). Since completion of motorway construction in June 2004th, there were 22 single-vehicle accidents on this section.

Accidents resulted in 3 fatalities, 6 people with serious injuries and 12 people with minor injuries. Unadjusted speed to road conditions was assumed as the cause of all accidents. According to available data, in all accidents only one vehicle was involved. Accidents have occurred at different times of the day but most of them happened in the afternoon, in the period between 4 and 8 PM. Also, the most accidents occurred in normal weather conditions (dry pavement, moderate wind).

This paper presents the research of the possible causes of accidents (in terms of road design and driver behaviour) on a hypothetical level. This means that the study contains assumptions (critical speed and driving manoeuvres) and there is no pretension that the conclusions are reliable and explain the real causes of the accidents.

Conducted research attempted to determine what is different in this section from the rest of the road alignment with similar geometric characteristics and traffic conditions, which leads to large number of accidents.

Single-vehicle accidents usually occur in the curves due to loss of vehicle control caused by exceeding the side (radial) friction or due to loss of vehicle stability caused by uneven deformation of front and rear tires.

In this research, the analysis of the road alignment on the concerned section was done first. Then test-drives were carried out with vehicle equipped with two devices (ball bank indicator and GPS data logger PerformanceBox) that are collecting data on driving characteristics (speed, longitudinal and radial acceleration, trajectories...). An the end, based on the data analyzes, the hypotheses about the possible causes of accidents were set out.

2 Analysis of the road alignment

The design speed for highway is \( V_p = 120 \text{ km/h} \). According to Croatian guidelines for the road design (2001), minimum radius of horizontal curve is \( R = 750 \text{m} \) using the maximum cross slope \( q = 7\% \). The minimum radius of crest vertical curve is \( R_{C\text{ min}} = 19000 \text{ m} \), and of sag vertical curve is \( R_{S\text{ min}} = 13000 \text{ m} \).

On the section concerned, there are two horizontal curves. Looking from west to east, the first curve has a radius \( R = 4800 \text{ m} \), 2707 m in length and the second one has a radius \( R = 4000 \text{ m} \), 559 m in length. On the west, from the junction Vrpolje to the section concerned, three S-curves with radius of 1400-1800 m are designed. After the section, toward to the junction Sitno, there is a curve with radius of 3500 m, 2185 m in length.

Vertical alignment of section consist of tangents with grades from 0.6% to 2% with sag curve radius \( R = 28000 \text{ m} \).

Accidents location and elements of the alignment on the analyzed section of highway are shown in Figure 1.
Figure 1 shows that accidents occurred at the flattest part of the route with the elements that far exceed the minimum values (horizontal radius of curvature, the radius of vertical curve).

Examination of project documentation showed that both curves have crown cross slope, which means that in the east-west direction curve with radius of 4800m has a negative cross slope and in west-east direction negative cross slope is designed in a curve with radius of 4000m. It was also found that the curves connection was projected without transition curves (spiral; clothoid).

According to two separate rules of Croatian road design guidelines, application of negative cross slope and design of S-curves without the transition curve is enabled for large values of the radius. Such a combination of the horizontal elements that allowed the use of both possibilities happened here at the same location.

3 Equipment

Two devices were used for the study: ball bank indicator and PerformanceBox.

The ball bank indicator is an inclinometer (accelerometer) that is used for the purpose of determining safe curve speeds for horizontal curves in the USA. It is a tube with the ball in a fluid. During the drive, ball deviates from the neutral position due to superelevation, body roll and radial friction. It measures the overturning force (side friction), measured in degrees, on a vehicle negotiating a horizontal curve. It is a standard operating instrument used by Federal and State Departments of Transportation.

One of the earliest ball-bank indicator studies was done by Moyer & Berry in the 1940s. They investigated ball-bank indicator readings as a measure of "centrifugal force", superelevation, speed and curvature.

In more recent studies, Carlson revisited methods to measure lateral acceleration in a banked turn. Carlson also mentioned that the influence of body roll is negligible for passenger cars while predicting the ball bank angle. Table 1 compares maximum side friction
factors recommended by Carlson (1995) with those from study by Moyer and Berry. Carlson recommends slightly higher maximum side friction factors than Moyer & Berry.

Table 1: Side friction factors and ball bank angle

<table>
<thead>
<tr>
<th>Ball bank angle (°)</th>
<th>$f_{des}$ by Moyer &amp; Berry</th>
<th>$f_{des}$ by Carlson model</th>
</tr>
</thead>
<tbody>
<tr>
<td>14</td>
<td>0.21</td>
<td>0.24</td>
</tr>
<tr>
<td>12</td>
<td>0.18</td>
<td>0.21</td>
</tr>
<tr>
<td>10</td>
<td>0.15</td>
<td>0.17</td>
</tr>
</tbody>
</table>

Beside the ball bank indicator, it was used another device named PerformanceBox. It is 10 Hz GPS data logger based on the Racelogic VBOX which is used by the majority of car and tire manufactures around the world to assess car and tire performance. PerformanceBox is a GPS based performance meter for measuring side forces, speed, braking distance and more. PerformanceBox tools software allows graphical analysis of acceleration (lateral and longitudinal), braking and cornering characteristics. The highway location can easily be export to Google Earth, Track Vision and other mapping software at various coordinate systems.

4 Field research

The research was carried with vehicle equipped with mentioned devices. There were made 4 test rides in each direction, from junction Vrpolje at chainage 334.5 km to the service area Sitno at chainage 343.5 km (9 km).

Speed limit on the highway is 130 km/h but operating speeds are higher.

Assuming that accidents occur because of speeding, test drives were carried out with speeds of 150-170 km/h, which correspond to 30 fastest recorded speeds during one day.

PerformanceBox collected data on speed, curve radius, radial acceleration, time and location every 1/10 second. Ball bank indicator data were video recorded with the time on the camera aligned with the time recorded with PerformanceBox. This allowed the precise determination of the location where the ball bank indicator showed high values of deflection that can be uncomfortable for the driver (over 10°). According to the Table 1, these deviations correspond to the values of the side friction factor from 0.15 to 0.17.

5 Presentation and analysis of the recorded data

Data recorded with PerformanceBox were processed and analysed using software PerformanceBox Tools (Figure 2). The figure shows the recorded data on the driving trajectory, turning radii, time elapsed, radial acceleration expressed in $g$...
Figure 2: Analyzed data from PerformanceBox Tools

Data on the geographical latitude and longitude were exported to Google Earth as well as data about locations where ball bank indicator values were greater than 10°, i.e. value of side friction were greater than 0.15 (0.17). These values have proven to be uncomfortable at speeds greater than 100 km/h.

From the data (Figure 2) one can see that there were no big values of radial acceleration on the transition between two curves, but there was a sudden change of radial acceleration (more than 1 m/sec²) what is few times greater than allowed.

At transitions between curves, PerformanceBox recorded the radial acceleration values of 0.15 m/sec². Since these locations have negative cross slope of 2.5%, the friction factor is around 0.175 which is close to the values recorded with ball bank indicator. It is also important to note that both devices recorded peaks at the same locations.

The recorded values of the radial acceleration should not be critical for dry pavement with a high-quality surface. For dry pavement and worn tires slip coefficient of friction is rarely less than 0.4. For wet pavement, depending on its macro texture, type and detritions of tires, slip coefficient of friction fall below 0.2 for high-speeds (Sandberg, U.; Ejsmont J, 2002).

According to the presented data on the available and the recorded values of side friction, it is almost unbelievable that the loss of vehicle control occurred due to skidding.

After all, on the locations out of the section concerned side friction factors from 0.15 to 0.19 have been recorded and no one accident occurred.

Therefore, the analysis of the data collected at all locations with high values of radial acceleration change has been performed.

On the section concerned, the greatest changes of lateral accelerations were recorded on 2 locations (showed in red circle on figure 1) on transition between two curves; one location for each direction of drive. First location is located about 130m west from connection point.
of curves with radii \( R = 4800 \text{m} \) and \( R = 4000 \text{m} \) and second location is about 100m east from the connection point.

Figure 2 shows the results from PerformanceBox for the first location. The minimum radius achieved due to transition between curvatures without spiral (and negative cross slope) was 1528 m what resulted with radial acceleration was 0.15 g. When driving from one to another curve radial acceleration is changed from 0 to 0.15 \( g \) (1.47 \( \text{m/sec}^2 \)) at an interval of 1.3 seconds (609.6 - 608.28 sec) resulting in radial acceleration change of 1.13 \( \text{m/sec}^3 \). Ball bank indicator recorded radial acceleration change of approximately 1.03 \( \text{m/sec}^3 \).

On second location, radial acceleration change was higher than 1.5 \( \text{m/sec}^3 \) i.e. 6 times higher than the allowed (0.25 \( \text{m/sec}^3 \)) for speed of 130 km/h. The test speeds were over 150 km/h so the recorded values are more indicative.

At locations outside the subject section the radial acceleration change values were well below 1 \( \text{m/sec}^3 \) and the differences in acceleration were significantly less because there were no change of curvature direction.

According to this findings, there is a possibility that at these two critical locations abrupt change in radial acceleration due to changes of curvature direction (without spiral) and the occurrence of negative cross slope surprised driver who reacted with inadequate manoeuvre which could lead to loss of vehicle control or stability due to uneven deformation of front and rear tires.

As well as radial acceleration change results in uncomfortable side impact, change in steer direction results with tire deformation. Besides radial acceleration \( a_c \), as a result of circular motion with constant speed \( V_x \), speed component \( V_y \) appears (due to tire deformation).

Figure 3 shows the so-called bicycle model [6] where \( \alpha_f \) and \( \alpha_r \) are slip angles of the front and rear wheels i.e. the angles between the longitudinal axis of the wheel and the direction of movement caused by tire deformation. \( V \) is the vehicle speed, \( V_x \) is a speed component in the direction of the longitudinal axis of the vehicle, \( V_y \) is the radial speed component, \( \beta \) is so-called side slip, i.e. the angle between the direction of the vehicle in the centre of gravity and the longitudinal axis of the vehicle, \( \delta \) is the steering angle, \( \omega \) is the angular speed, \( F_{yr} \) and \( F_{yf} \) are the friction forces on the front and rear wheels formed at the contact of wheel and pavement.
At low speeds, the steering angle is \( \delta = \frac{L}{R} \), where \( L \) is the wheelbase length. At higher speeds, because of cornering forces and deformations, steering angle is equal to:

\[
\delta = \frac{L}{R} + \alpha_f - \alpha_r
\]  

Tire deformation i.e. side slip and slip angles depend on the tire characteristics and pressure, weight on wheels (if the engine is front or back), acceleration... Deformation caused by the change of curvature leads to further acceleration of the wheels which in some cases can lead to loss of vehicle stability. Vehicle behaviour depends on the ratio of the slip angles of the front and rear wheels. If the angels are equal, then driver should not change the steering angle during acceleration in the curve i.e. \( \delta = \frac{L}{R} \) (neutral steer). In case when \( \alpha_f > \alpha_r \), during increasing speed in a curve driver should increase steering angle (understeer). In case when \( \alpha_f > \alpha_r \), increasing speed decreases radius of movement and driver needs to reduce the steering angle (oversteer).

The most dangerous situation is when \( \alpha_f > \alpha_r \) because circular movement increases the radial acceleration and reduces turning radius, which further increases radial acceleration and further decreases radius what can lead to the loss of vehicle stability and turning in the direction of the radial force. Larger deformation of rear wheels can occur due to several reasons: the performance of vehicles (e.g., rear engine), as a result of shifting vehicle weight to the front wheels on steep grades (rear tires have to deform more in order to achieve the same frictional resistance), due to braking because of weight transfer to the front wheels, due to the lower pressure in the rear wheels than the front ones...

We calculated vehicle dynamic for bicycle model considering cross slopes and load distribution over front and rear axle simulating recorded trajectory of test vehicle. Results showed that for speeds over 185 km/h and braking more than 3 m/sec\(^2\) (due to driver surprise because of negative cross slope at the transition between two curves without spiral)
could led to the vehicle oversteer i.e. losing of vehicle stability and an single-vehicle accident when rear tires are somewhat underinflated (cca 20%).

6 Conclusion

This paper tried to determine and analyze the possible causes of 22 accidents which occurred on Zagreb-Split highway, from km 339 to km 342. Comparing the characteristics of this section to the adjacent parts of the route in a length of about 10 km, it has been found that this is the flattest part of the route with the largest radii of curvature (R = 4800 and R = 4000m), which may encourage motorists to drive faster. Selection of large radius led to the application of negative cross slope of a curve and the design of alignment without spirals between curves. Test rides made with the highest recorded speed on a nearby highway’s section showed that the application of a negative cross slope in the curves with a direct connection without spirals resulted in a smaller driving radius (R < 1500) than the projected one and radial acceleration change several times higher than the allowed values. This acceleration change could surprise drivers and result in inappropriate manoeuvres (sudden jerk the wheel or braking), which could lead to the loss of vehicle stability. The calculation of vehicle’s motion equations simulating recorded vehicle manoeuvres at a higher speed was made. Calculation showed that the case of sudden manoeuvres with increased slip angle on the rear wheels (which can occur due to characteristics of the tires and braking) leads to loss of vehicle stability and continuous increase of the radial acceleration and angular speed of the vehicle’s vertical axis.

Literature


Croatian guidelines on the basic requirements that a public road outside the village and their elements must comply with the security of transport, 2001. Ministry of Transportation.


