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SIGHT DISTANCE ANALYSES IN ROAD DESIGN PROCESS: SERBIAN PRACTICE

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Abstract. New Serbian policies on road design introduce the concept of operating speeds. Decades ago, national policies were based on the constant design speed concept. Among other design parameters, in relation to that constant design speed, minimum radii of horizontal and vertical road geometry were determined. Introduction of the operating speed concept provides for more realistic prediction of speed levels along the road. Unlike the constant design speed, operating speed levels vary along the road, reaching higher levels in curves with larger radii, on straight sections and on reverse curves and dropping down to the design speed level in horizontal curves with the minimum radius. Consequently, besides a constant Stopping Sight Distance (SSD), which is calculated from the constant design speed, the new term, Required Sight Distance (RSD) is introduced. RSD varies along the road, as it is calculated from the operating speed, which also varies along the road. Appropriate RSD analyses are crucial on road rehabilitation projects, since a simple resurfacing that enables higher speed levels, without providing increased RSD, may hamper the safety of a newly resurfaced road. Software tools for predicting operating speed levels and optical analyses of the road are also presented in this paper. Software tools for RSD analyses enable the import of lines of sight into the 3D model of the roadway and their export into the cross sections extracted from the model, thus facilitating the obstacle removal. Also demonstrated are tools for determining Available Sight Distance (ASD), which are based on triangulated 3D models of the roadway as well.

Keywords: road design; sight distance; stopping sight distance; passing sight distance, required sight distance; available sight distance; design speed; operating speed.

Introduction

Like many relevant policies on road design throughout the world, current Serbian policies (Putevi Srbije 2011), published in 2011, consider several types of sight distance: Stopping Sight Distance (SSD), Passing Sight Distance (PSD) and Available Sight Distance (ASD).

At any spot along the road, the driver of a vehicle travelling at the design speed needs the minimum sight distance to observe a potential obstruction on the pavement and perform the breaking action, stopping the car safely before reaching the obstacle. This distance is named SSD. To safely execute the passing manoeuvre on a two-lane road, the driver needs a much longer sight distance, named PSD. Finally, ASD is the length of the road visible to the driver.

At any point along the road, ASD must be greater than or, at least, equal to SSD. In addition, to provide for an adequate level of service, at a certain percentage of the road ASD must be greater than PSD (Highway Capacity Manual 2010).

In the latest release, Serbian policies on road design introduce the concept of operating speeds, the concept adopted from the German design practice (FGSV 201:2012). The concept is based on the assumption that the actual operating speed of a vehicle is equal to the design speed only in critical curves with radii equal to the minimum radius specified for that particular design speed. As the road is always designed with the curves having the radii greater than or equal to the critical one, the actual operating speed would be higher than the design speed in all curves with the radii greater than the critical one.

While the analytical prediction of operating speed levels in Serbia is strictly based on German methodology (FGSV 201:2012), some research has been undertaken in neighbouring countries to experimentally underpin the whole process. Some studies concentrate on estimating free flow speed levels (Dell'Acqua *et al.* 2011) and identifying particular 'black spots' caused by the poor design co-ordination of the alignment, while

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others focus on acceleration and deceleration rates of vehicles approaching and leaving the curves (Esposito *et al.* 2011; Dell'Acqua, Russo 2010). Recent experimental study (Dell'Acqua 2015) has demonstrated that driver behaviour can be modelled during the design phase in order to predict the speeds that will actually be found on two-lane rural roads.

Unlike the design speed, which is a constant value, the operating speed changes along the road, reaching higher levels in greater radii, and having lower values in tighter curves. Consequently, SSD, which is calculated for the specific design speed, is not enough for the vehicle travelling at the higher speed (operating speed) to execute the sudden stop in an emergency. As a result, a new kind of sight distance, Required Sight Distance (RSD), is introduced. Mathematically, RSD is derived by using the same formula used for calculating SSD. However, unlike SSD, which is calculated from the constant design speed and is constant along the road, RSD is calculated from the actual operating speed, which fluctuates along the road. As the actual operating speed changes its value along the road so does the RSD, reflecting the more realistic SSD requirements of the driver.

While RSD practically replaces SSD in most parts of the road design process, PSD remains unchanged. According to Serbian policies (Putevi Srbije 2011), PSD is still calculated from the constant design speed and not from the operating speed levels.

No specific method of calculating the fourth type of sight distance, ASD, is recommended in the current policies. Though a small nation, there have been many active software developers in Serbia in the last two to three decades and many companies engaged in road design and construction have been developing their own software solutions (Gavran 2002, 2008, 2012). As a result, many leading design bureaus in Serbia have been deploying a full 3D concept for almost two decades. 3D environment provides an ideal, if not the only practical, method for determining ASD along the road.

The purpose of this paper is to concentrate on methods of calculating RSD and ASD along the road. The calculation of RSD relies on operating speed analyses, while determining ASD is based on illustrative 3D techniques.

Integrating speed and sight distance analyses is of the utmost importance, especially on road rehabilitation projects. By simply resurfacing the road, drivers are often enabled (if not encouraged, or provoked) to drive at higher speeds. In such cases, not providing adequate RSD, meeting the needs of motorists travelling on a newly resurfaced road, may lead to an increase in the number of accidents.

In essence, sight distance analyses are more specific to two-lane roads than to dual carriageways. The general geometry of a typical dual carriageway provides for much longer ASD. For example, because of the gentle longitudinal grades applied, changes between the successive grades are smoothed out by using vertical radii much larger than those resulting from the speed analyses. In plan projection and in cross section view, potential lateral obstacles are moved further away from the driver. In addition to the stopping lane and the shoulder, if in cut, the dual carriageway is usually accompanied by wide ditches, displacing the cut slope away from the motorist. What is more, the absence of oncoming vehicles completely redefines, if not excludes, PSD analyses. In the case of a dual carriageway, sight distance analyses, as a part of broader optical analyses of the road, are often transformed into aesthetic analyses.

1. Stopping Sight Distance (SSD)

The drivers travelling at the specified design speed must be provided with the sufficient sight distance, enabling them to safely stop the vehicle, should the obstacle appear on the road surface. That distance is named SSD and must be assured at any point along the road.

The concept of calculating SSD is illustrated in Fig. 1. After observing the obstacle (be it another vehicle, pedestrian or simple road debris), it takes some time for the driver to undertake any action (breaking, evasive manoeuvre etc.). This time is known as reaction time. During that time, the driver perceives the problem, extracts critical details, assesses the risk and decides what to do, while the vehicle travels at a design speed, covering a considerable distance.

The reaction time is usually 2 seconds long (FGSV 201:2012). Only after that time, does the breaking action take place. To bring the vehicle from the design speed to a full stop requires a breaking distance. The formulas in Fig. 1 are based on speed V in km/h, while distances are produced in metres. Active breaking forces come from the longitudinal friction (coefficient of longitudinal friction f) and from the rolling resistance (usually 2% or 0.02 of the vehicles gross weight). Coefficient of longitudinal friction f is speed dependent. It drops from 0.44, for the speed of 40 km/h, to 0.27, for the speed of 130 km/h (Putevi Srbije 2011). Adopting the lower value

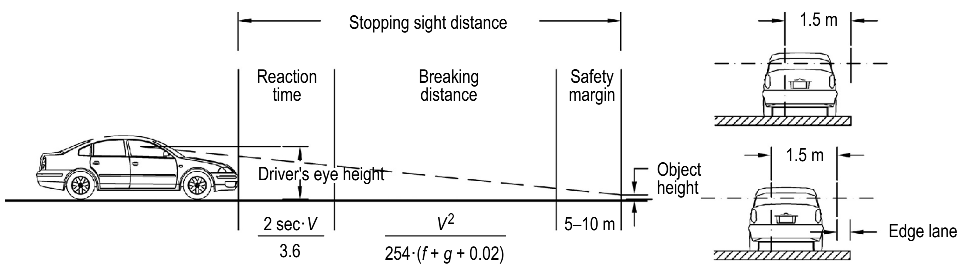

Fig. 1. Calculating SSD

of *f*, the one which refers to the speed *V* at which the driver commences braking, is being on the 'safe side', as it lengthens the SSD. In essence, while slowing down from speed *V* to zero, coefficient *f* changes its value from low, for speed *V*, to high, for speed close to 0.0 km/h. Positive longitudinal grade (upgrade) *g* shortens the breaking distance, while negative grade (downgrade) does the opposite. Finally, a safety margin 5–10 m long (Putevi Srbije 2011) is added to produce the total SSD.

While checking if the line of sight is intercepted by some obstacle (side slope, shrub or pavement surface on a crest vertical curve), it is assumed that the line of sight starts from the driver's eye, positioned 1.1 m above the pavement surface and 1.5 m from the right edge lane. The line of sight ends at the object on the pavement surface, which is only 10 cm tall, representing the simple road debris.

2. Passing Sight Distance (PSD)

To execute the passing manoeuvre on a two-lane road, the driver must be assured that there is no traffic from the opposite direction at the distance equal or greater than PSD. PSD is illustrated in Fig. 2. The black vehicle executes the passing manoeuvre at the speed that is ΔV higher than the speed of the slower vehicle. The slower vehicle, as well as the one from the opposite direction, travels at the design speed *V*. The entire passing manoeuvre is completed in time Δt. Serbian policies set the ΔV at 15 km/h and the Δt at 10 s (Putevi Srbije 2011).

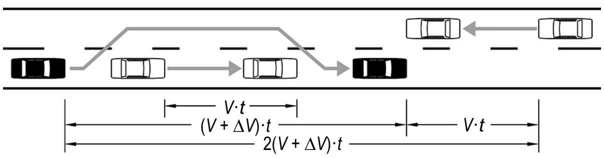

Fig. 2. Calculating PSD

While SSD must be assured at any point along the road, PSD should be provided at some sections of the road only. Based on the category of the road and the topography, the minimal percentage of the road with the ASD exceeding PSD is also set by the policies (Putevi Srbije 2011). This minimal percentage provides prerequisites for the adequate level of service.

3. Required Sight Distance (RSD)

Even in countries renowned for the discipline of local drivers (Riffel, Zimmermann 2011), the speed of the vehicle on a rural road is governed rather by the geometrical elements of the road, than by speed limits indicated on traffic signs.

The minimum radius of the road is decided in relation to the specified design speed. This minimum radius is usually applied at the critical sections of the road only, while larger radii are applied elsewhere. It is logical to expect the driver to negotiate curves with the minimal radii at speeds that are close to the design speed and to use larger radii to their advantage, travelling at higher speeds.

The relation between the radius of a horizontal road curve and the speed is given in Fig. 3. It is assumed that the vehicle negotiating the curve travels at the speed retrieved from the diagram no matter what the design speed is. Therefore, it is recommended not to reduce the pavement cross grade even in larger radii. For example, if the design speed is 80 km/h and the minimum radius for 80 km/h is 250 m, the speed of the vehicle in $R = 250$ m would really be 80 km/h. But, if the radius of 450 m is applied somewhere along the road, the speed of the vehicle negotiating that radius would be 100 km/h, as 450 m is the minimum radius for the design speed of 100 km/h. Relation between the design speed and the minimum radius is based on the maximum cross grade of 7%. If, in $R = 450$ m, the vehicle would travel at the design speed of 80 km/h, the cross grade could be reduced below 7%. However, assuming that the vehicle negotiates $R = 450$ m at 100 km/h, it is best to leave the cross grade at 7%.

Only when the speed of the vehicle is impeded by the excessive longitudinal grade, could the cross grade of the pavement be reduced. Fig. 4 shows the relation between the longitudinal grade and the speed. The speed of the passenger car is unaffected by the longitudinal grade if it falls between −5% (downgrade) and +4% (upgrade).

Based on the previous assumptions, the operating speed along the road is presented in the form of a diagram (Fig. 5). In general, the diagram of the operating speed is derived from two other diagrams, one representing speed levels in relation to elements of horizontal geometry, the other representing speed levels in relation to the vertical geometry of the road.

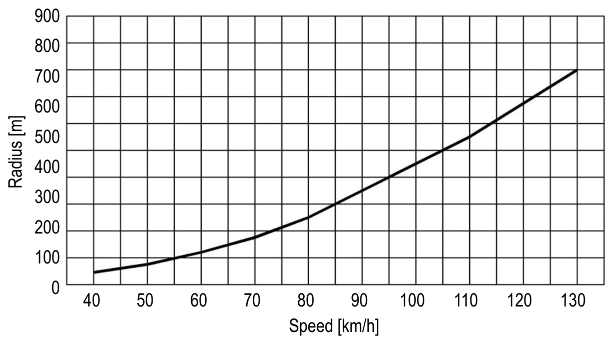

Fig. 3. Relation between the radius of a horizontal curve and the speed (Putevi Srbije 2011)

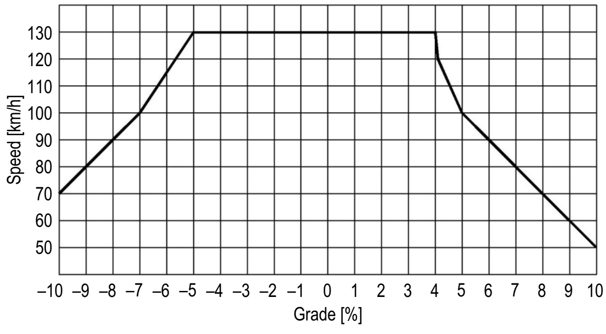

Fig. 4. Relation between the longitudinal grade and the speed (Putevi Srbije 2011)

Fig. 5a shows how the speed changes in relation to the horizontal geometry of the road. In each curve (ARC) the operating speed equals the maximum speed level for that particular radius (as shown in Fig. 3). While covering the distance between two successive arcs (reverse curve or straight section), the vehicle first accelerates and, after reaching the peak speed, decelerates down to the speed level required for safely negotiating the next curve. Acceleration and deceleration rates are equal 0.8 m/s^2 (Putevi Srbije 2011, FGSV 201:2012).

In years preceding, the latest issue of Serbian policies for road design, operating speed analyses were recommended, but not mandatory. Acceleration rate was set at 0.5 m/s^2, while deceleration rate was 1.0 m/s^2. As a result, diagrams depicting the operating speed based on the horizontal geometry were slightly different for opposing directions of the road. With acceleration and deceleration rates being equal (0.8 m/s^2), these two diagrams are identical.

The process of determining operating speed levels in plan projection is further clarified in Fig. 6. Each straight section (LINE) or curve (ARC) has its own operating speed level (as read from the diagram in Fig. 3). That speed level is constant throughout the element (LINE or ARC) and represented by a thick horizontal line. While approaching that element, the vehicle decelerates at the rate of –0.8 m/s^2. After leaving that element, the vehicle accelerates at the rate of 0.8 m/s^2, producing the symmetrical speed curve. Practically, the operating speed level for a particular element (ARC or LINE) is characterized by a shape consisting of three elements: deceleration curve, horizontal line and acceleration curve. The shaded area left below these intersecting three-element shapes represents speed levels. LINEs and ARCs with large radii are somehow specific, as corresponding operating speed levels are high, requiring no deceleration before the element and disallowing acceleration after the element. In these cases, speed shapes are reduced to horizontal lines, with no deceleration/acceleration curves.

Fig. 5b–c illustrate how the vertical alignment of the road affects operating speed levels. Fig. 5c represents the longitudinal profile with the crest curve in the middle and two excessive longitudinal grades on both sides. Speed levels in Fig. 5b are determined from the relation shown in Fig. 4 (speed–longitudinal-grade relation). In this case, speed diagrams differ for opposite directions of the road – the thick continuous line represents the speed of a vehicle travelling forward (to the right), while the dashed line represents the speed of a vehicle travelling back (to the left).

Finally, by superimposing speed levels resulting from the longitudinal profile over speed levels coming from the horizontal geometry of the road, total speed levels are produced. The thick continuous line in Fig. 5d shows how the speed of a vehicle travelling forward is being reduced by features of the longitudinal profile. The dashed line in Fig. 5e shows the total speed levels for a vehicle travelling back. Thus, final operating speed diagrams, Fig. 5d and Fig. 5e, are given for both directions of the road. From these two diagrams, RSD are calculated for both directions of the road.

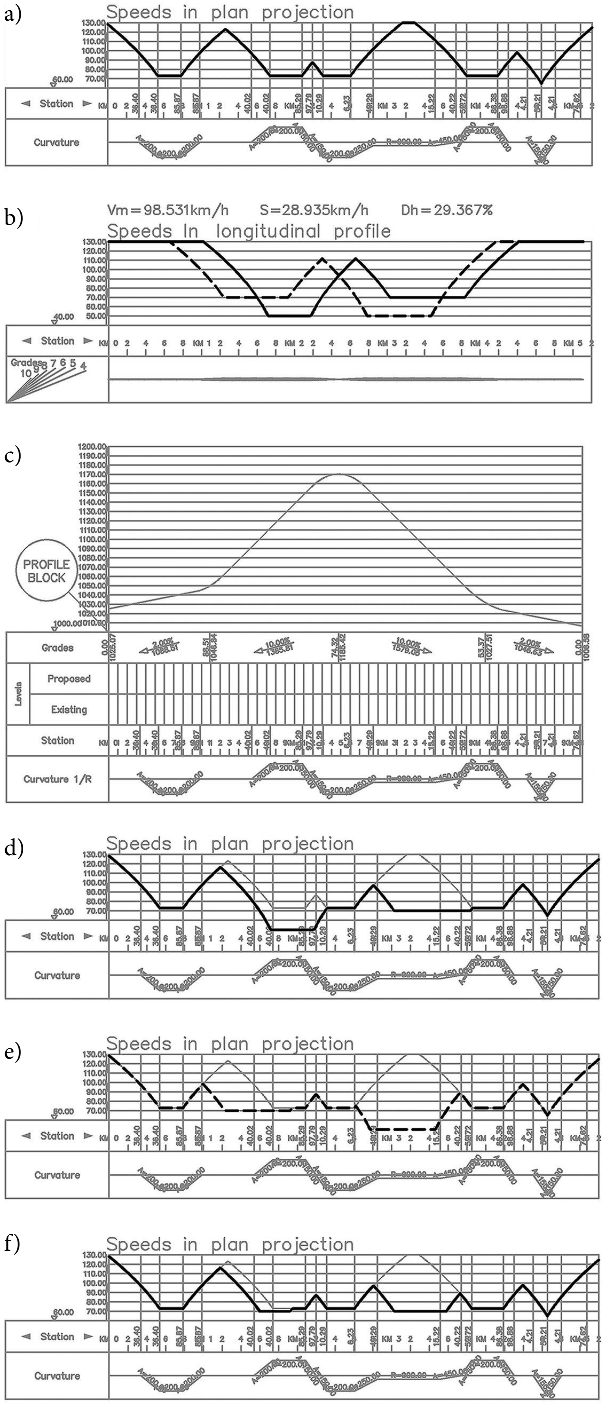

Fig. 5. Operating speed levels calculation

However, before proceeding to RSD analyses, one more activity has to be completed. And this activity is related to the pavement cross grade. In this particular case, excessive longitudinal grades affect speed levels for both directions of the road, resulting in two different speed level diagrams. At any spot along the road, the pavement cross grade is unique for both sides of the pavement (left and right) and must satisfy the higher of the two speed levels (from two opposite directions of the road). Therefore, the diagram representing the higher of the two speed levels has to be constructed first.

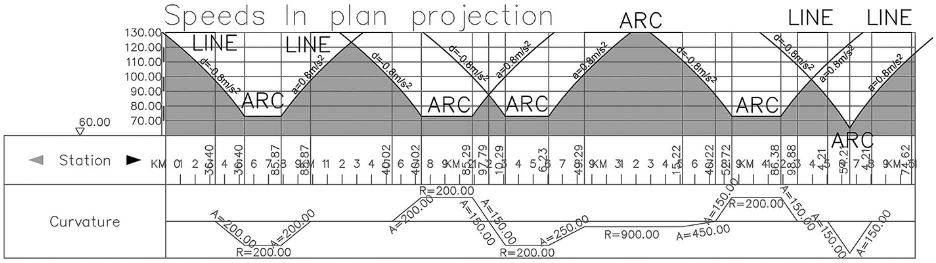

Fig. 6. Calculating operating speed levels in plan projection

The diagram is shown in Fig. 5f. In this case, with speed levels resulting from the horizontal geometry reduced by longitudinal grades, pavement cross grades in some of the curves are reduced (in relation to maximum 7% cross grade). Resulting (reduced) cross grades are derived from speed levels coming from Fig. 5f and corresponding radii.

As for the RSD calculation, total operating speed diagrams for both directions of the road, Fig. 5d and Fig. 5e, are used to calculate sight distances. RSD values are not constant along the road. These values are calculated from the simple model represented in Fig. 1, by entering specific operating speed levels instead of a constant design speed *V*. As the operating speed changes along the road, so does the RSD.

Now, sight distance analyses turn into 3D. At stationing steps (intervals) where RSD values have been calculated, physical lines of sight are now imported. These lines of sight are physically represented by lines starting at specific driver's positions (1.1 m above the pavement surface and 1.5 m from the right edge lane) and ending at RSD in front of the corresponding driver's positions. The end of the specific line of sight is attached to the 0.1 m tall obstacle (representing the road debris), resting on the pavement 1.5 m from the right edge lane. The import of lines of site is illustrated in Fig. 7. Lines are imported into the triangulated 3D model of the roadway. In Serbia, this kind of model, surpassing an ordinary TIN (Triangulated Irregular Network) model, has been in use for two decades. The model consists of both 'open' (terrain, top surface of the road) and 'closed' (pavement layers, pipes, tunnels, bridges, houses) surfaces.

In Fig. 7, lines of sight for vehicles travelling in opposite directions are represented by using different line types (thick continuous and dashed lines). Once imported into 3D, lines of sight could be easily transferred into cross sections. Cross sections are literally cut out from the triangulated model (Gavran 1996, 2012). Various features of the roadway (the road itself, retaining walls, houses, pipes, etc.), if triangulated, could be cut by vertical planes representing cross sections. Within a particular cross section, each triangulated object is represented by a set of lines. These lines are intersecting lines between specific triangles and a cross section's vertical plane (Fig. 8).

To incorporate lines of sight into cross sections extracted from the model, mathematical tools for cross sections' extraction had to be simplified (Gavran 1996). In fact, cutting the lines by cross sections' vertical planes is way simpler than cutting the triangles. While the cutting of triangles with a vertical plane results in penetration lines, the cutting of lines results in penetration points.

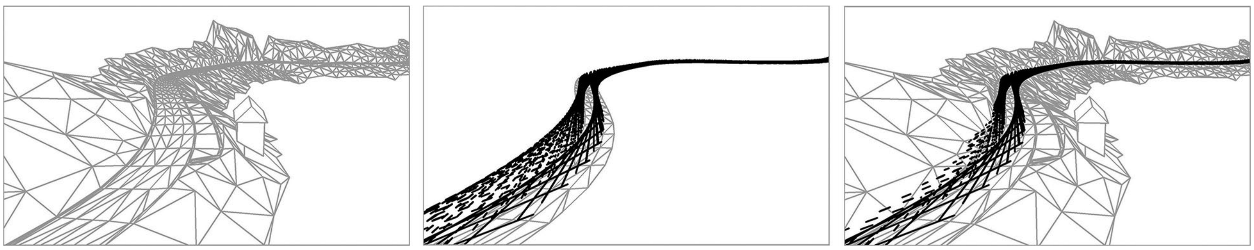

Fig. 7. Importing lines of sight into the triangulated model

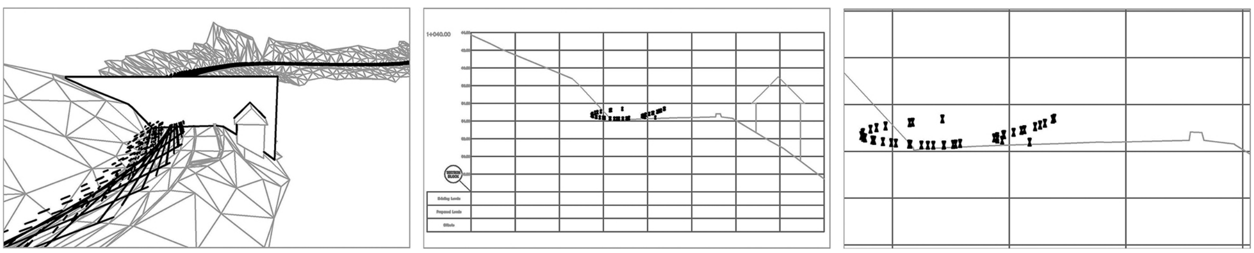

Fig. 8. Transferring lines of sight penetration points into cross sections

With lines of sight penetration points being transferred to extracted cross sections, it becomes clear that RSD values in Fig. 8 are not satisfied. Lines of sight are being launched from the driver's eye positions towards objects resting on the pavement surface at the distance RSD in front of the driver. And within the extracted cross section on Fig. 8, penetration points of these lines lay beyond the cut slope on the left side of the road (inner side of the curve). It means that, the cut slope must be moved further inside the curve to provide for RSD.

Within a specific cross section, lines of sight penetration points resemble the burst of bullets fired from an automatic rifle. Points at elevations closer to the driver's eye come from lines just launched from the driver's position. These points represent lines of sight whose starting points lie just before the particular cross section. On the other hand, points closer to the pavement surface represent lines of sight whose ending points (imaginary obstacles on the pavement surface) lie just beyond the cross section.

RSD analyses based on operating speed levels are crucial, especially when applied on road rehabilitation projects. If not accompanied by adequate RSD analyses, simple road resurfacing projects, providing higher riding comfort and higher operating speeds, might result in an increase in traffic accident rates.

According to police records (Ministarstvo unutrašnjih poslova Republike Srbije 2008), in the Serbian region of Mačva only, after road rehabilitations in 2007, the traffic accident rate jumped by 37%, while casualty rate increased by 69%, in the following year. Even worse, after rehabilitating the road section Kragujevac–Ravni Gaj (Kragujevac is the major industrial city in central Serbia) in 2005, the accident rate in the two following years increased by 150%, with a 375% increase in casualty rate.

4. Available Sight Distance (ASD)

ASD stands for the length of the road visible to the driver. At any spot of the road, ASD must be greater than RSD and, to provide for an adequate level of service, ASD must be greater than the PSD at the certain percentage of the road.

3D CAD environment provides the best, if not the only practical, method for determining ASD. As shown in Fig. 9, ASD values could be retrieved from the triangulated 3D model of the road. An imaginary vehicle (driver's eye) moves along the road. The driver eye stays 1.1 m above the road surface and 1.5 m from the right edge lane, as shown in Fig. 1. As the vehicle advances along the road, lines of sight are launched in sequences from each of the driver's eye positions towards potential obstacles. While the driver's eye stays at the particular station, the lines of sight are launched in sequence towards obstacles resting on the pavement surface at the specific stationing intervals in front of the driver. Obstacles are usually 0.1 m tall and are positioned 1.5 m from the right edge lane. While keeping the driver's eye in place and starting from the obstacle located at the station closest to the driver (just in front of the driver), the program checks whether the line of sight penetrates some of the triangles forming the model of a roadway. When the program encounters the penetration, it stops, records the length of the previous line of sight as an ASD and moves the driver's eye to the next station.

To provide for ASD analyses, the triangulated 3D model of the roadway must incorporate two strings of points (Fig. 10). These points (string A and string B) indicate positions of obstacles at specified stationing intervals.

At the same time, from these two strings of points, the driver's eye positions could be retrieved as well. While the height of a potential obstacle is 0.10 m, the driver's eye travels 1.10 m above the pavement surface (or 1.00 m above obstacle positions). Right string (string A) in Fig. 10 indicates obstacles (and indirectly driver's eye positions) for a vehicle travelling forward, while left string (string B) indicates obstacles for a vehicle travelling in the opposite direction – 'back'.

However, complex at first glance, the algorithm underpinning ASD calculation is quite simple and the resulting programming code is very short. Algorithm in Fig. 11 takes the specified string of points (*string*1) and performs ASD calculation. The data structure of a point from a string contains the station at which the point resides, as well as the coordinates *Xj, Yj, Zj* of the point itself.

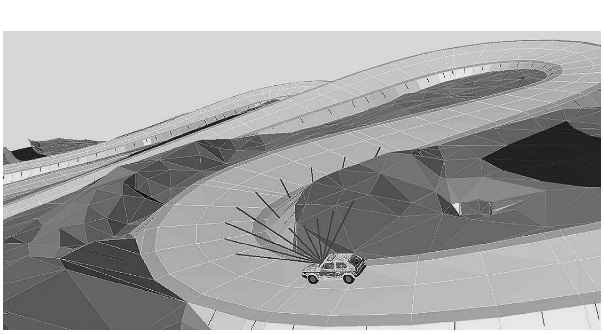

Fig. 9. Retrieving ASD from the model

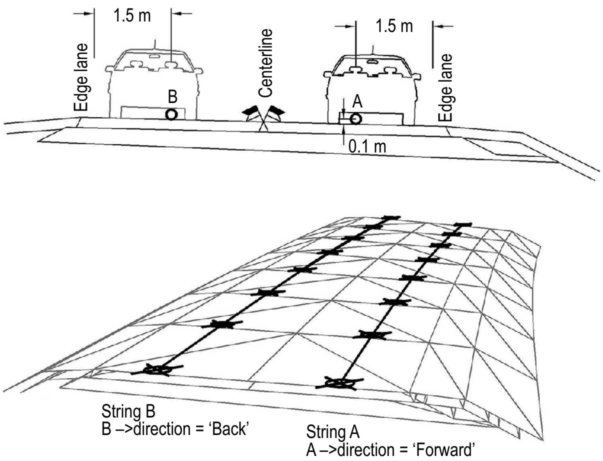

Fig. 10. 3D modelling for ASD analyses

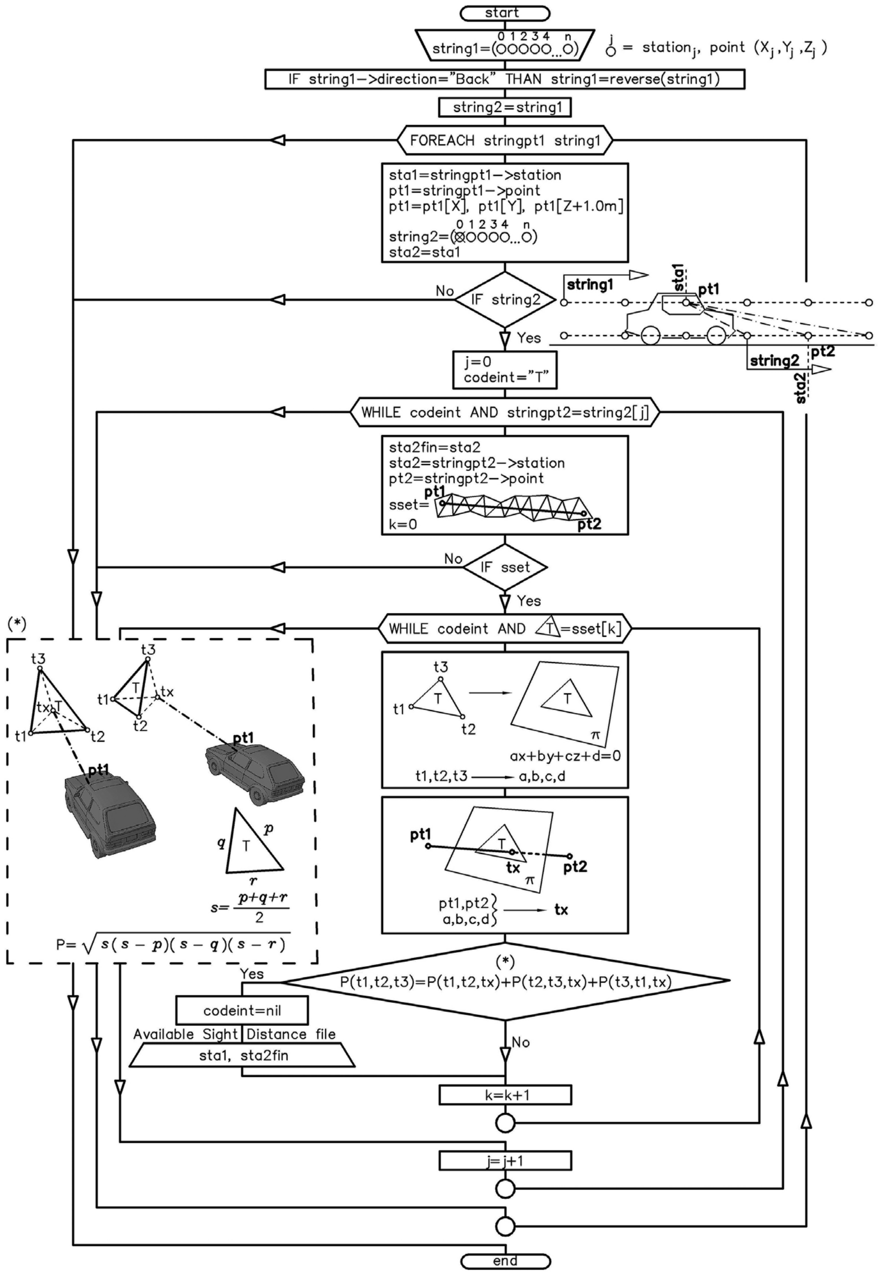

Fig. 11. Algorithm for calculating ASD from the triangulated 3D model

In general, *string*1 is supposed to be a string indicating the trajectory of the driver's eye, while *string*2 is supposed to be a trajectory of potential obstacles. Input string, *string*1, is reversed if it depicts the vehicle driving 'back' (string B in Fig. 10).

The program takes points (*stringpt*1) from *string*1 one by one and retrieves from them the driver's eye positions. For each (FOREACH) point *stringpt*1, the program retrieves station *sta*1 and the point *pt*1 itself in coordinate terms. Then, the coordinate *Z* of point *pt*1 (pavement surface + 0.10 m) is moved for 1.0 m upward, thus reaching the driver's eye position which is 1.10 m above the pavement surface. Each time the program takes point *stringpt*1 (and *pt*1) from *string*1, the first point from string *string*2, which is supposed to be the string of obstacles, is deleted. Thus, while advancing along the driver's eye positions (*string*1), the program reduces the string of potential obstacles (*string*2) only to those remaining in front of the driver.

Through the WHILE cycle that follows, the program takes points (*stringpt*2) from *string*2 one by one. From each point *stringpt*2, the program retrieves the station *sta*2 and the point *pt*2 itself, in coordinate terms. Each point *pt*1 (at the station *sta*1) acts as the driver's eye position, while each point *pt*2 (at the station *sta*2) acts as a potential obstacle. For each point pt1, the WHILE cycle takes all remaining points *pt*2 in front of the driver in sequence. The program (WHILE cycle) steps through *pt*2 points until the penetration of the line connecting *pt*1 and *pt*2 (line of sight) through the triangulated model is encountered. For each *pt*1, the initial value of *codeint* is set to *T*. When penetration is encountered, *codeint* is set to *nil* (destroyed), signalling the end of ASD calculation for a particular driver's eye position *pt*1.

At the very start of the first (outer) WHILE cycle, variable *sta*2*fin*, which is supposed to be the farthest station visible from station *sta*1 is set to the value of station *sta*2. The initial value of *sta*2 is the first station in front of *sta*1. As the starting point of the line of sight is tied up to point *pt*1, its ending point steps through points *pt*2. To speed up the process of searching for a potential penetration of the line of sight through the triangles, the program first isolates triangles located in the immediate vicinity of a particular line of sight, thus reducing the set of candidate triangles to be analysed. This set of 3D triangles is *sset*.

Then the inner (nested) WHILE cycle checks each triangle from *sset* against the line connecting *pt*1 and *pt*2 for a potential penetration. For each triangle *T* from set *sset*, the program retrieves its vertices *t*1,*t*2,*t*3 and calculates parameters *a*, *b*, *c*, *d* of a plane π containing the triangle *T*. Then the potential penetration point *tx* of a line connecting *pt*1 and *pt*2 (connecting the driver's eye position and the obstacle) though plane π is found. In essence *tx* always exists, unless the line connecting *pt*1 and *pt*2 is parallel to π. However, real penetration of the line of sight *(pt*1*–pt*2*)* through triangle *T* exists only if *tx* resides within the triangle *T*. The fastest way of checking whether *tx* resides within triangle *T* with vertices *t*1,*t*2,*t*3 is to compare the area of triangle *t*1,*t*2,*t*3 to the areas of three subtriangles: *t*1,*t*2,*tx*, *t*2,*t*3,*tx* and *t*3,*t*1,*tx*. If the area of *t*1,*t*2,*t*3 equals the total area of three subtriangles, then *tx* resides within *t*1,*t*2,*t*3.

The next problem is how to quickly calculate the area of a triangle with vertices *t*1,*t*2,*t*3 given in coordinate terms. There are formulas that are simple and very quick to execute, dealing not with the triangles themselves, but with the triangles' projections, for example in *xy* plane. However, if the triangle *T* is a vertical one, formulas dealing with horizontal projections of the triangle *T* and its subtriangles are useless. Unlike the genuine TIN model, widely used in road design, where 3D triangles cannot be vertical or overlapping, the concept presented herein is designed to tackle even these special triangles. In many cases, vertical triangles representing columns of overpasses, facades of nearby buildings or vertical retaining walls present the major visual obstacle. Therefore, Heron's formula, calculating triangle's area *P* from its sides *p*, *q* and *r* and the semi-perimeter *s* has to be deployed.

Once the penetration point of the line of sight *pt*1*–pt*2 though the triangulated model is encountered, *codeint* is set to *nil* (destroyed), moving the analyses to the next driver's eye position. As the obstacle at the current station *sta*2 cannot be seen from driver's eye station *sta*1 (penetration exists), the stationing pair *sta*1, *sta*2*fin* is written into the database. At this point in the program, station *sta*2*fin* is still set to the previous obstacle position *sta*2, which is visible from station *sta*1. The stationing pair *sta*1, *sta*2*fin* means: the driver positioned at station *sta1* could see the obstacle on the pavement surface positioned as far as the station *sta*2*fin*. At the end of the program, for each driver's eye position (*sta*1), the farthest visible station *sta*2*fin* is clearly indicated, thus reporting how the ASD changes along the road.

For ASD determination purposes, it might be quite appropriate to create the simplified model of the road, instead of creating the detailed model of an entire roadway (Fig. 12). In essence, in favourable road conditions, with no significant obstacles surrounding the road, lines of sight starting from the driver's eye might extend to unrealistically distant stations. In theory, for the driver negotiating a horizontal curve, with no obstacle obscuring the view, the line of sight might leave the section of the road in front of the vehicle and wander all the way to the opposite side of the curve, even if such a line of sight ends up completely off the general travel direction. Thus, in some cases, it is more realistic to generate the simplified model of the road surface, accompanied by imaginary side obstacles. Side obstacles, preventing the line of sight to wander uncontrollably, might coincide with potential lines of trees, shrubs, grass and similar temporary or permanent obstacles. Relevant national policies and guidelines (Putevi Srbije 2011; FGSV 293/3:1983; SN 640090b:2001-07; SN 640140:1978) set the minimum lateral distance for such obstacles in relation to the pavement edge.

Fig. 12 shows the simplified model of the road accompanied with imaginary side obstacles. In the right part of the figure, critical lines of sight, the shortest ones launched from a particular station and resulting in a penetration, are given as well.

At the end of the calculation, ASD values for both directions of the road are stored in a file. Both ASD and RSD values could be drawn in a single form (Fig. 13). The upper portion of Fig. 13 shows the speed diagram (and the diagram of curvature) for the model shown in Fig. 12. Its lower portion shows RSD and ASD curves for both directions of the road. In curves, ASD values are slightly above RSD values (as expected). In reverse

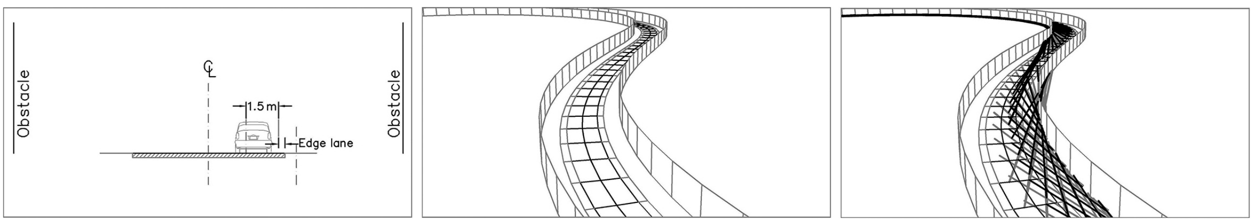

Fig. 12. Retrieving ASD from a simplified model of the road

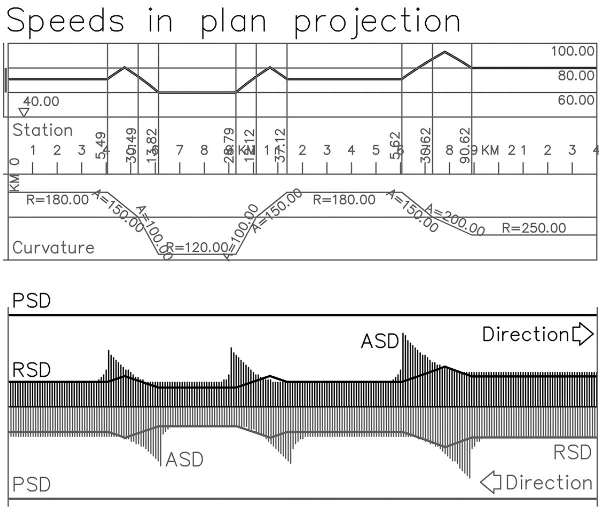

Fig. 13. Comparing required, available and PSD

curves, the field of view opens widely in front of the driver, as ASD greatly surpasses RSD. Due to curvature of the centreline, there is no portion of the road allowing the passing manoeuvres (ASD is always below PSD).

While domestically developed 3D software solutions for sight distance analyses are predominant in Serbia (Gavran 2012), there are several worldwide standards in this field, which are based on different CAD platforms. These are, for example, AutoCAD Civil 3D (Autodesk, AutoCAD and Civil 3D are registered trademarks of *Autodesk Inc.*), MXROAD (MXROAD is trademark of *Bentley Systems Inc.*) and AutoTURN Pro 3D (AutoTURN Pro 3D is a trademark of *Transoft Solutions Inc.*), etc.

Conclusions

New Serbian policies on road design introduce the concept of the operating speed and relate the optical analyses of the road to this concept. Unlike the Stopping Sight Distance (SSD), which is constant along the road and is based on the constant design speed, the newly introduced Required Sight Distance (RSD) varies along the road.

RSD is equivalent to the SSD, but is calculated from the more realistic operating speed, which changes its value along the road, reaching higher levels in larger radii, on straight sections and in reverse curves and dropping down to the design speed only in critical curves with the minimum radius.

The paper concentrates on RSD and ASD (Available Sight Distance) analyses. While explaining the RSD concept, the analysis of the operating speed is given as well. Recent research (Riffel, Zimmermann 2011) shows that even in countries renowned for the discipline of local drivers, the speed of the vehicle on a rural road is governed rather by geometrical elements of the road than by speed limits indicated on traffic signs. Therefore, it is of the utmost importance to assess realistic operating speed levels as early as the design stage and to provide for necessary RSD.

Appropriate operating speed analyses, accompanied with the RSD analyses, are crucial on road rehabilitation projects. By simply resurfacing the road and enabling vehicles to travel at higher speeds, the rate of traffic accidents might even increase, if necessary analyses of operating speed levels are not carried out and measures to provide for appropriate RSD are not undertaken.

Software tools, integrating operating speed analyses and RSD analyses, are demonstrated as well. These also include the tools importing lines of sight into the 3D model of a roadway and exporting the lines of sight into cross sections, thus facilitating the obstacle removal.

ASD analyses are demonstrated on triangulated roadway models, as 3D CAD systems provide the only practical method of determining these distances.

Some research has already been completed in order to further improve the concept of calculating more realistic operating speed levels in Serbia (Fric 2014) and abroad (Bella 2006; Spacek 2000, 2005; Fitzsimmons *et al.* 2013). Namely, in shallow horizontal curves, with relatively small turn angles, there are considerable discrepancies between the radius of the centreline and the real radius of the vehicle's trajectory. In shallow curves, drivers are able to follow the radius larger than the radius of the centreline, while still staying within their own traffic lane. Speeds of these vehicles are higher than those specified for nominal centreline radii (Fig. 3). So, the current research is oriented towards determining real trajectories and real speed levels in curves, especially in shallow ones. The results obtained will refine the prediction of operating speed levels in horizontal curves, thus improving RSD analyses.

References

Bella, F. 2006. Effects of driver perception of combined curves on speed and lateral placement, in *TRB 85th Annual Meeting Compendium of Papers CD-ROM*, 22–26 January 2006, Washington, DC, 1–15.

Dell'Acqua, G. 2015. Modeling driver behavior by using the speed environment for two-lane rural roads, *Transportation Research Record: Journal of the Transportation Research Board* 2472: 83–90. http://doi.org/10.3141/2472-10

Dell'Acqua, G; De Luca, M.; Mauro, R.; Lamberti, R. 2011. Motorway speed management in Southern Italy, *Procedia – Social and Behavioral Sciences* 20: 49–58. http://doi.org/10.1016/j.sbspro.2011.08.010

Dell'Acqua, G.; Russo, F. 2010. Speed factors on low-volume roads for horizontal curves and tangents, *The Baltic Journal of Road and Bridge Engineering* 5(2): 89–97. http://doi.org/10.3846/bjrbe.2010.13

Esposito, T.; Mauro, R.; Russo, F.; Dell'Acqua, G. 2011. Speed prediction models for sustainable road safety management, *Procedia – Social and Behavioral Sciences* 20: 568–576. http://doi.org/10.1016/j.sbspro.2011.08.063

FGSV 201:2012. *RAL – Richtlinien für die Anlage von Landstraßen*. Köln: Forschungsgesellschaft für Straßen- und Verkehrswesen, 136 S. (in German).

FGSV 293/3:1983. *RAS LG-3 – Richtlinien für die Anlage von Straßen – Teil: Landschaftsgestaltung (RAS LG) Abschnitt 3: Lebendverbau*. Köln: Forschungsgesellschaft für Straßen- und Verkehrswesen, 40 S. (in German).

Fitzsimmons, E. J.; Kvam, V.; Souleyrette, R. R.; Nambisan, S. S; Bonett, D. G. 2013. Determining vehicle operating speed and lateral position along horizontal curves using linear mixed-effects models, *Traffic Injury Prevention* 14(3): 309–321. http://doi.org/10.1080/15389588.2012.701356

Fric, S. 2014. *Teorijsko i eksperimentalno istraživanje graničnih trajektorija vožnje u vangradskim putnim krivinama*: doktorska disertacija. Građevinski fakultet, Univerzitet u Beogradu. 162 l. (in Serbian).

Gavran, D. 2012. *GCM++ (GAVRAN – Civil Modeller). User Guide*. Autodesk. 86 p.

Gavran, D. 2008. 3D based road design, in *10th International Conference on Applications of Advanced Technologies in Transportation 2008*, 27–31 May 2008, Athens, Greece, 8: 6537–6551.

Gavran, D. 2002. Road Design in 3D: Moving from 2D to 3D, in *Proceedings of the 3rd IRF Road Congress for South-East Europe*, 30 September – 3 October 2002, Belgrade, Serbia and Montenegro, 1–12.

Gavran, D. 1996. *Razvoj metodologije i tehnoloških postupaka za prostorno projektovanje aerodroma*: doktorska disertacija. Građevinski fakultet, Univerzitet u Beogradu. 252 l. (in Serbian).

Highway Capacity Manual. 2010. Transportation Research Board. 5th edition. 1650 p.

Ministarstvo unutrašnjih poslova Republike Srbije. 2008. *Indikatori bezbednosti saobraćaja dobijeni iz službenih policijskih zapisnika iz regiona Mačve i Kolubare* [Road safety indicators obtained from official police records in the region of Mačva and Kolubara]. 45 l. (CD-ROM). (in Serbian).

Putevi Srbije. 2011. Pravilnik o uslovima koje sa aspekta bezbednosti saobraćaja moraju da ispunjavaju putni objekti i drugi elementi javnog puta, *Službeni glasnik Republike Srpske* 50: 210–289. (in Serbian).

Riffel, S. B.; Zimmermann, M. 2011. Modellierung des Fahrverhaltens in Kurven, in *Kolloquium für Fortgeschrittene*, 9 Februar 2011, Karlsruhe, Deutschland, 1–17. Available from Internet: http://www.ise.kit.edu/rd_download/SEB/Kolloquium_SEB_11-02-09_Sven_Riffel.pdf

SN 640090b:2001-07. *Projektierung; Grundlagen; Sichtweiten*. (in German).

SN 640140:1978. *Linienführung; Optische Anforderungen*. (in German).

Spacek, P. 2005. Track behavior in curve areas: attempt at typology, *Journal of Transportation Engineering* 131(9): 669–676. http://doi.org/10.1061/(ASCE)0733-947X(2005)131:9(669)

Spacek, P. 2000. Track behavior and accident occurrence in curves on two-lane highways in rural areas, in *2nd International Symposium on Highway Geometric Design*, 14–17 June 2000, Mainz, Germany, Paper No. 002/67: 288–298.