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THE SPEED FACTOR IN SWEPT PATH ANALYSIS

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Abstract

The determination of the geometric vehicle movement is significant for the appropriate design of a road element, such as an intersection or a parking lot, because it ensures safe, smooth and without abrupt changes movements especially for heavy vehicles. Consequently, the accurate and correct swept path analysis of the vehicles determines the geometry of the horizontal alignment. Also, the selection of the design vehicle is a factor that affects the geometric characteristics of the analysis. The AASHTO Green Book presents the minimum turning paths, the maximum steering angle and the minimum centerline turning radius (CTR) for typical design vehicles. In order to simplify the geometrical problem of swept path analysis, the speed in sharp curve road is considered to be low and more specifically less than 15 km/h. However, this condition does not represent the actual vehicle movement, gap that the present paper aims to bridge by performing swept path analysis for increased travel speeds. There are only few cases, especially along urban road network that the lateral force applied on the vehicles that traverse horizontal transition curves are neglected due to low travel speed. On the contrary, in other road projects the transition curve is an integral design element and have advantages in geometric regularity of heavy vehicles movement because of their steering mechanism. Based on the literature review, in this study the design vehicles paths which are considered as clothoid shapes are correlated with their corresponding travel speeds. The implemented methodology considers various design vehicles which travel in various speeds, performing U-Turns.

Keywords: swept path, turning path, speed

1 Introduction

Swept path analysis is predominantly a geometry-based approach due to the fact that tire mechanics, in most situations have insignificant effect to offtracking simulation. Apparently offtracking is highly correlated with the travel speed of the vehicle under investigation. Particularly the more the speed travel the more the centrifugal forces acting on the turning vehicle. Nevertheless, this effect results in less offtracking distances and hence low-speed offtracking analysis errs on the side of safety [1]. Consequently, in low-speed offtracking approach, the problem is transformed to a pure geometrical one whilst in high-speed approach more variables have to be taken under consideration. The fundamental assumption in low-speed swept path analysis is that the truck driver is capable of steering from a straight line to a circular arc immediately without traversing a transition path, for instance a clothoid. This assumption however is not valid in high speeds and hence a comprehensive analysis should take into account the path curvature as well as the travel speed of the design vehicle [2], [3]. It is very well known that the path of any point of the front axle of a vehicle traversing a circular curve is an arc whereas the path of any point of the rear axle is a tractrix. Between the

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tangent and the arc, the shape of the vehicle's path the so-called transition path, depends on two primary conditions: the steering speed and the speed of the vehicle itself. Although many researchers stated that a clothoid describes better the said transition path, it has been documented that this is valid only under certain circumstances [4]. Therefore, the knowledge of the steering and travel speed of any vehicle negotiating a roundabout is of paramount importance in order to design a safe circular intersection or evaluate an existing one. Besides as inferred by Mussone et al [5], the use of simulation software packages, which provide efficient swept path analysis, combined with proper speed prediction models is a very handy tool to investigate the performance of a roundabout. They also mention that design consistency evaluation of road elements like roundabouts are predominantly based on the fluctuation of the vehicles' operating speed [5].
The interaction between travel speed and traversed path was one of the subjects examined in a research study conducted by Wolfermann et al [6] who aimed at developing a model in order to predict the speed profiles of turning vehicles at signalized intersections. They concluded that the approach, exit and minimum travel speed is related to the traversed path of the vehicles and consequently to the intersection's properties. The developed model encompassed the influence of the driving behaviour and other parameters to the speed profile of the vehicles [6]. Likewise, few years later Park et al [7] concluded that the assumption of identical traversed paths in roundabouts is not realistic. Case studies in several intersections in US and Japan revealed that as the turning manoeuvres increase so do the path variation [7].
In 1986 Sayers [8] summarized the research studies conducted until then regarding the developed offtracking models. He also proposed a graphical method to simulate swept path analysis of any type of vehicle negotiating any type of turn at low speed using Apple II computer. However, it was stated that the designers employed methods which were not capable of calculating low speed offtracking for transient paths [8] e.g. horizontal curves without transition segments where truck rollovers might occur [9].
The magnitude of speed is highly correlated with accidents frequency especially when it is accompanied with steering manoeuvres either abrupt or not e.g. curved road sections, intersections, roundabouts etc. The combination of speed and steering, results in rearward amplification which poses a great problem to multiunit vehicles. When the rearward unit of the vehicle is overamplified the vehicle overturns [10]. Multi trailer trucks are more likely to exceed rollover thresholds compared to semitrailers [11]. Apparently, the contribution of superelevation and suspension system is substantial with regards to the prevention of this phenomenon [12]. Moreover, poor braking efficiency of unload trucks in conjunction with the lower frictional capabilities of truck tires compared to passenger car's ones pose a great risk for the truck drivers who negotiate roundabouts in higher speeds [13].
A study conducted in Kentucky [14] revealed that double trailers trucks are more likely to be involved in overturning accidents compared to single unit trucks. However, the latter have higher accident likelihood at intersections [14]. The size and the number of the articulation points affect the offtracking and safety performance of large vehicles. For instance, a very effective measure to increase the stability of the large vehicles is the enlargement of their width which enhances the rollover resistance [15] whereas long vehicles of few articulation points are associated with greater low-speed offtracking [11]. The latter is critical when designing roundabouts, intersections and sharp horizontal curves where low speeds are to be expected [16].
The three different types of offtracking analysis i.e. low speed, high speed steady and high speed transient offtracking, are implemented individually and in combination, in an 8-axle vehicle in a research study from New Zealand [17]. The authors showed that depending on the travel speed and the radius of the turn the offtracking of the vehicle might be more than twice its width. In general, low travel speeds and small radius of turn force the vehicle to

off-track more. It is also confirmed that the magnitude of offtracking also depends on the number of the articulation joints of the vehicle meaning that the more the number of the joints the less the offtracking [17].
In the present paper, the offtracking in low speed and high-speed steady will be investigated. In a U- Turn the large vehicles travel at low speed because of the small turn radii. Therefore, in order to achieve increased speed, a U- Turn form with a clothoid transition curve will be used.

2 Methodology

2.1 U-Turn and clothoid paths

In the present paper, a U- Turn form is used, namely a 180º turn that has 14.46 m radius of circular arc. The geometry of the form is based on the minimum turning path template of single-unit truck (SU-12 [SU-40]) according AASHTO Green Book 2011 [18]. The choice of this form was made, because it can accommodate different types of vehicles, such as passenger cars, single unit trucks, semi- trailer trucks and buses, without overstepping the max steering angle of each design vehicle.
Generally, the speed of vehicles that move in U- Turn, is less than 15 km/h according AASHTO Green Book 2011 [18] due to constant change of deflection angle. Hence, in order to increase vehicle's speed, a steering path configuration using straight lines, clothoids and a circular arc is considered. Clothoid is a transition curve with linear change of its curvature relative to its length. Because of its geometry clothoid also allows the increasing change of deflection angle and therefore the low maintenance of turn rate. In addition, clothoid permit the smooth application of the centrifugal force and consequently the driving comfort. For that reason, in this research clothoids are used as the transition sections between straight lines and circular arcs in order to approach the path that the vehicle drivers probably choose to travel in high speeds in U- Turns.

2.2 Swept path analysis

As design vehicles a passenger car (P-Car), a single-unit truck with total length 9.14 m (SU-9), a single-unit truck with total length 12.04 m (SU-12) and an intercity Bus with total length 13.86 m (BUS-14) are used according AASHTO Green Book 2011 [18]. Two turning paths are assumed in a U- Turn form that are the same for all design vehicles. The first steering path has the following form: two straight lines in the entry and the exit of the form that tangentially connect with a circular arc of 14.46 m radius. The second steering path has the following form: two straight lines in the entry and the exit of the form that tangentially connect with clothoids with parameter A = 15 and length L = 16.50 m, which are tangentially connected to a circular arc of 13.64 m radius.
The steering path concurs with the design of the centerline of the front axle. The description of the path that the rear axle of a vehicle follows for a given steering curve is called tractrix of the steering curve and is described by a complex curve. The swept path analysis estimates the paths of the front and the rear wheels and ultimately the off- tracking of the vehicle.
In the present paper, the swept paths are generated in Anadelta Tessera software that is considered the most accurate according to the researchers [19]. The basic theory of the program is that the rear axle is computed on the straight line that connects the middle of the step distance with the old location of the rear axle (Fig.1) [19].

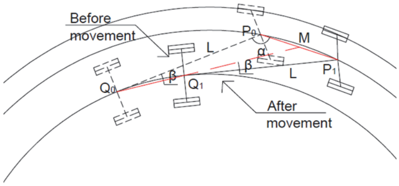


Figure 1 Calculation method of offtracking

2.3 Speed estimation

The implementation of the swept path analysis requires the calculation of the steering angle in each step. Subsequently, in each path position the turn rate R is estimated using the following equation:

$$R = \frac{STA_2 - STA_1}{PL_2 - PL_1} \tag{1}$$

where STA_1(º) and STA_2(º) are the steering angles in the initial and in the final position of the step path respectively, and PL_1(m) and PL_2(m) are the path length angle in the previous and in the present position of step path respectively.

Subsequently, the maximum turn rate maxR of the path is selected and the design speed V (km/h) can be determined by the following equation [20]:

$$\max R = \frac{\max STA}{V \cdot t} \Rightarrow V = \frac{\max STA}{\max R \cdot t} \tag{2}$$

where maxSTA (º) is the max steering angle path and t (s) is the lock to lock time.
Lock to lock time t is considered for all types of design vehicles equal to 6 s.

3 Results & Analysis

3.1 Swept path analysis

The swept path analysis described in Chapter 2.2 depends on the design of the steering path. The Fig. 2 and Fig. 3 show the swept path analysis for each design vehicle using a steering path form with and without clothoid.

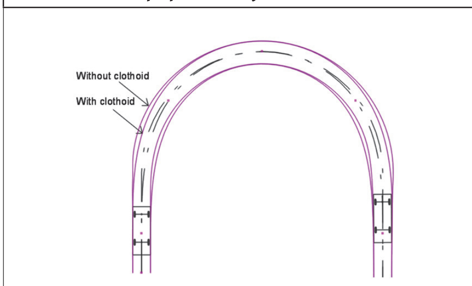
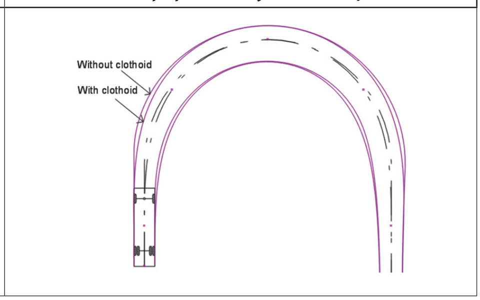
Swept path analysis for P- Car	**Swept path analysis for SU-9**
	

Figure 2 Swept path analysis for P-Car and SU-9

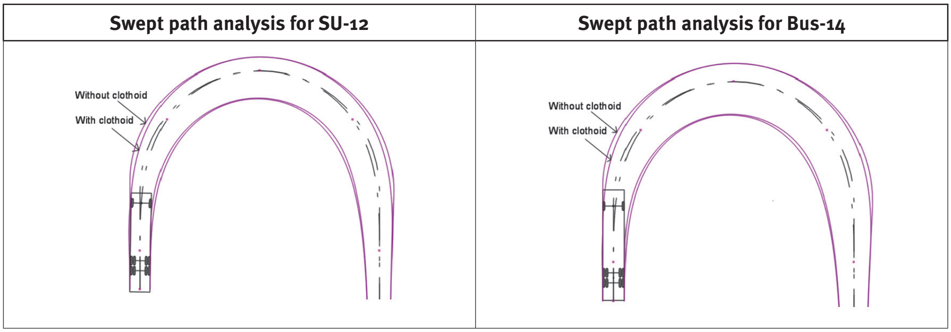


Figure 3 Swept path analysis for SU-12 and BUS-14

Swept path analysis of the four design vehicles show that the off tracking in the steering path without the use of a clothoid is greater than the offtracking in the steering path with the use of a clothoid. In addition, in this U- Turn form the intercity bus (BUS-14) takes up the greatest width when turning compared to the other design vehicles because of its great length (13.86 m).

3.2 Speed analysis

The design speeds are calculated according to the swept path of the design vehicles (Fig. 2, Fig. 3) i.e. the maximum turn rate is defined for each steering path (with and without clothoid). The speeds of the design vehicles are estimated according the Eq. (2). as well, the difference of the speeds between the U-Turn form without the use of clothoid and with the use of clothoid.The results are encompassed in Table 1.

Table 1 Speed analysis for design vehicles

Design vehicle		U- Turn form without clothoid		U- Turn form with clothoid		
		maxR	Speed [km/h]	maxR	Speed [km/h]	Dif. (%)
Passenger Car	maxSTA[^{0}] 31.60	3.82	9.93	0.86	44.27	3.46 %
SU-9	maxSTA[^{0}] 31.8	3.88	9.83	1.47	25.91	1.64 %
SU-12	maxSTA[^{0}] 31.8	3.90	9.79	1.75	21.86	1.23 %
BUS-14	maxSTA[^{0}] 45.2	3.91	13.89	1.91	28.37	1.04 %

According to the Table 1, the estimations of speeds in U- Turn form with clothoid are greater than in U- Turn form without clothoid. The passenger car has the greatest difference between the speed values. The intercity bus develops the highest speed of the large vehicle's despite of its great length.

4 Conclusion

According to the preceding investigation, the following conclusions can be drawn for the movement of vehicles in U- Turn and their speed estimation:

- The steering path using a clothoid allows higher speeds than that of the steering path without a clothoid.
- The use of a clothoid reduces the off-tracking distance in all of the design vehicles.
- The application of a clothoid permits the large vehicle to follow the steering path at speeds greater than 21km/h with an increase in the turn rate. Hence, the maximum steering angle has a significant impact in the speed estimation.
- Clothoid geometry permits the increased change of the deflection angle and therefore the turn rate kept small. The smaller the maximum turn rate, the higher the design speed.

The preceding analysis reveals that the precise tracking of a vehicle performing a U-Turn has not be determined yet and consequently further research is recommended on this topic. Finally, this research can be very helpful to designers, who deal with the movement of vehicles at roundabouts, U-Turns, vehicle parking and intersections, as well to developers of swept path analysis simulation software tools.

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