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Geometric Design Issues and Safety Analysis of Two-way Rural Road Tunnels

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Abstract

Rural road tunnels may pose specific issues from several perspectives: mainly environmental, geotechnical/structural (excavation methods), economical. Geometric road design is then an often arduous task, which should be conducted by trying to make trade-offs between the different issues, and at the same time, it should be compliant to relevant standards and regulations. Nevertheless, the safety of road tunnels should be preserved, not only considering technological systems (e.g. ventilation systems, emergency exits and paths), but also regarding traditional road-safety issues related to road geometric features. In fact, the analysis of recent accident data related to two-way two-lane rural road tunnels has revealed that accident frequencies/rates in two-way two-lane rural road tunnels are comparable with those on the corresponding open sections, even with some differences concerning the accident types. Since road safety issues may be exacerbated by geometric design inaccuracies, some relevant road tunnel geometric issues are discussed in this study. These issues, scarcely treated in previous research and not addressed in detail in technical documents, emerge from the match between different design needs. In detail, those relate to: 1) the possible need for variable road tunnel cross-sections in case of lane/shoulder widenings for the sake of improving visibility or for other reasons, or in case of lay-bys, 2) the possible need for climbing/overtaking lanes in case of steep downhill or uphill slopes. An attempt at addressing the mentioned problems is provided, based on relevant existing research and technical documents. In particular, the preliminary design stages leading to a "WES" (Without Enlargement Solution) solution are described. Hence, besides enlarging the research body in this specific field, the study is also potentially deemed useful for practitioners who have to face similar design problems.

Keywords: Two-way road tunnels, Road tunnel geometric design, Tunnel safety

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1. Introduction

The design of road tunnels should be compliant with specific standards, which are usually different than standard for open roads in most prescriptions. For example, in Europe, the EU Directive 2004/54/CE should be taken into account, together with its local implementations. It mainly provides prescriptions for the road safety and risks of tunnels belonging to the Trans-European road network, while specific road standards are not addressed in detail. Hence, there are several specific geometric conditions in which designers do not have exact guidelines on how to define the different road elements.

In detail, the modification of the cross-section inside the road tunnel leads to several technical and practical difficulties. Considering the traditional construction methods, main difficulties are related to the realization of the tunnel covering and to the different formworks needed. For automated or semi-automated construction methods (such as the TBM method with the Tunnel Boring Machine or the NATM method -New Austrian Tunnelling Method-), issues are related to the early stage of the excavation. In fact, the gradual variation of the cross-section, such as for curve widenings for visibility (or other) reasons, or for the implementation of lay-bys or supplementary lanes, will lead to the difficult application of these modern construction methods. For this reason, specific solutions are needed in these cases, such as technical measures or other surrogate measures (i.e. considering markings or lighting conditions). These technical problems should be assessed in parallel with more space needed by the enlarged cross-section and then with an increase in the environmental impact and the costs of the road tunnel.

Since accidents in road tunnels may have dramatic consequences and entail evacuation of people (Ronchi et al., 2012), the preservation of optimal road safety conditions should be always maintained. Several studies in the scientific literature are dedicated to safety issues of multi-lane one-way tunnels (see e.g. Caliendo et al., 2013), while less research is present which investigates into road safety of two-way two-lane rural road tunnels. Hence, in this study, geometric design issues and road safety analyses are specifically related to this type of road tunnels.

The remainder of this paper is organized as follows. In the first part, the analysis of accident data related to two-way two-lane rural road tunnels, which are rarely considered for safety analyses, is conducted. This is aimed at assessing the magnitude of safety issues related to these tunnels. Once a general overview of safety problems in road tunnels is so provided, the specific analysis of some relevant geometric design issues which may result in safety problems, and for which research and technical prescriptions are scarce, is conducted. Some conclusions based on the analysis performed and the geometric design issues analyzed are drawn at the end of the article.

2. Analysis of Italian two-way two-lane rural road tunnel accident data

The accident data analysis is based on Italian data as a case study. Italian two-way two-lane rural road accidents were derived from the ACI-ISTAT dataset including the most recent 5-years period available: 2013-2017. The list of road tunnels taken into account for the investigation was derived from De Guglielmo (2008). It is a collection of road tunnels managed by the main Italian road agency ANAS. The road tunnels selected for the analysis are bi-directional (single carriageways, two lanes), more than 1000 m long.

After, based on the information reported in the selected dataset, tunnels were geographically localized and accidents were matched with the road name and kilometer information. Accidents are localized with a 1-km precision in the open-source dataset considered. Hence, only the accidents which could have surely been localized inside the road tunnel were considered for the analysis. In addition, a 300 m tolerance in localizing accidents from the tunnel entrance/exit was considered, to avoid discharging accidents which may have been influenced by the tunnel. The considered distance comes from the 10-seconds rule used in the EU Directive (2004) for locating a cross-section variation at convenient distances from the tunnel. In this specific case, a design speed of 100 km/h was considered and the estimate was rounded, thus leading to a distance of 300 m.

The analyzed dataset is composed of 70 road tunnels, with total length of about 130 km. The mean length of road tunnels is 1851 m (st. dev.: 937 m). On this network, 348 fatal and injury (FI) accidents were recorded. The main descriptive statistics of the analyzed road tunnel accidents are reported in Table 1.

The analysis of descriptive statistics in Table 1 are useful for a comparison with similar data of generic two-way two-lane rural roads. A previous study by the authors was based on a network of 74 Italian two-way two-lane rural road segments, about 213 km long, with mean traffic volume 6507 vehicles/day (st. dev.: 4269 vehicles/day) (Colonna et al., 2016). In this study, the average crash frequency is 0.44 FI accidents/year/km (st. dev.: 0.51 FI accidents/year/km) and the average crash rate is 0.16 FI accidents/millionvehicleskm (st. dev.: 0.15 accidents/millionvehicleskm). Hence, the comparison with tunnel accident data for similar roads suggests that frequency and crash rates are similar, even if data are more dispersed for tunnels (higher standard deviations). This could be due to specific tunnel features which may be particularly influential on the accident occurrence in some cases, thus implying a higher variability in accidents. However, it should be noted that traffic volumes are significantly higher in the sample of tunnels. Hence, since the relationship between traffic volume and accident may be non-linear (e.g. more than linear) for high traffic volumes (e.g. Sacchi et al., 2012; Colonna et al., 2016), tunnel accident rates may be even smaller than rates for similar roads. Actually, this was suggested in other sources (e.g. Lemke, 2000).

Table 1. Descriptive statistics of accidents (2013-2017) in the road tunnels investigated

Variable	Descriptive statistics
Tunnel length	Mean length: 1851 m (st. dev.: 937 m), Total length: 129.6 km
Severity	18 Fatal accidents (F, 5.2 %), 330 Injury accidents (I, 94.8 %)
Mean crash frequency	0.50 FI accidents/km/year (st. dev.: 0.68 FI accidents/km/year) 0.03/0.47 F/I accidents/km/year (st. dev.: 0.06/0.67 F/I accidents/km/year)
Traffic volume	Mean volume: 14297 vehi./day (st. dev.: 10273 vehi./day)
Crash rate	0.16 FI accidents/millionvehicleskm (st. dev.: 0.35 FI accidents/millionvehicleskm) 0.01/0.15 F/I accidents/millionvehicleskm (st. dev.: 0.03/0.35 F/I accidents/millionvehicleskm)
Vehicles involved*	166 accidents with only 4-wheels light vehicles involved (47.7 %), 129 accidents with at least one motorcycle involved (37.1 %), 53 accidents with at least one commercial/industrial vehicle involved (15.2 %)
Accident types**	36 head-on accidents (10.3 %), 118 angle/lateral accidents (33.9 %), 85 rear-end accidents (24.4 %), 52 run-off accidents (14.9 %), 6 accidents with pedestrians involved (1.7 %), 42 “other” accidents (12.1 %)

*accidents with only 4-wheels light vehicles involved were computed as the difference between total accidents and the accidents in the other two categories recorded
**percentages computed on the accidents for which types were recorded (9 accidents having unknown type)

For what concerns accident types, they are compared with mean estimates from ISTAT accident data (sample 2013 data, for rural one carriageway two-way roads excluding intersections). In this case, there is a notable difference especially in rear-end (24.4 % in tunnels versus 15.8 % on open roads data) and run-off accidents (14.9 % in tunnels versus 30.5 % on open roads, see also Montella and Imbriani, 2015). The lower percentage of run-off accidents may be due to lower speeds and curvature, and to the closed tunnel environment, which typically impedes run-offs; while the higher percentage of rear-end accidents may be due to lower headways and incorrect evaluation of distances.

Whereas, the distribution of accidents within the road tunnel is reported in Fig. 1. Actually, there are only 7 tunnels in the dataset with length > 2 km. The percentages were computed over tunnels with length, namely, 3-4 km and 5-6 km. It is possible to note from Fig. 1 that accidents specifically cluster in the kilometre of tunnel entrance/exit in the case of tunnels with length 3-4 km. This was actually expected from previous research (see e.g. Amundsen and Ranes, 2000). The result of 5-6 km tunnels is less clear, but it is referred to only 2 tunnels, thus being scarcely explanatory.

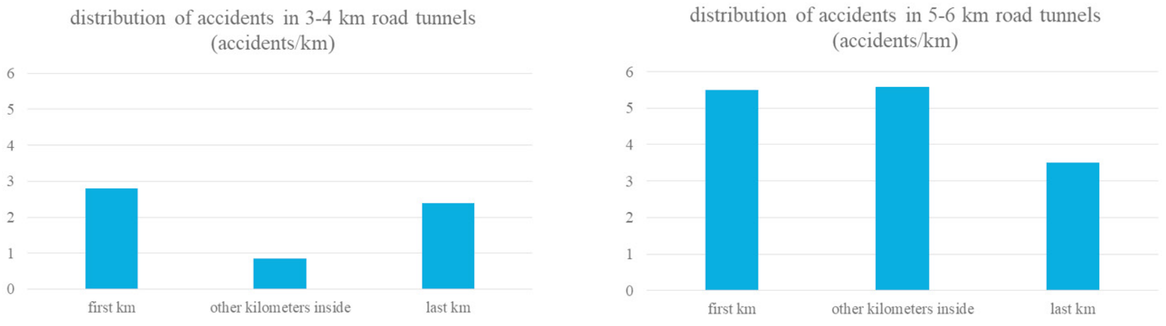

Fig. 1. Distribution of accidents in the kilometers of the road tunnels investigated (first kilometer, last kilometer, other kilometers inside)

Finally, a preliminary traffic volume-accident frequency relationship is reported in Fig. 2. It was obtained after having excluded some outlier data of accident frequencies (Fig. 2, left) highlighted from plotting accident frequencies data into a boxplot. There is a very weak relationship between traffic and accident data, with several data being largely dispersed from the regression line. However, several other variables should be considered for accident predictions besides traffic volumes and more accident data should be needed for the development of detailed accident prediction models. Note however, that potential accident prediction models for two-way two-lane rural road tunnels should be anyway matched with traditional safety analyses (see e.g. Colonna et al., 2018) with appropriate modifications.

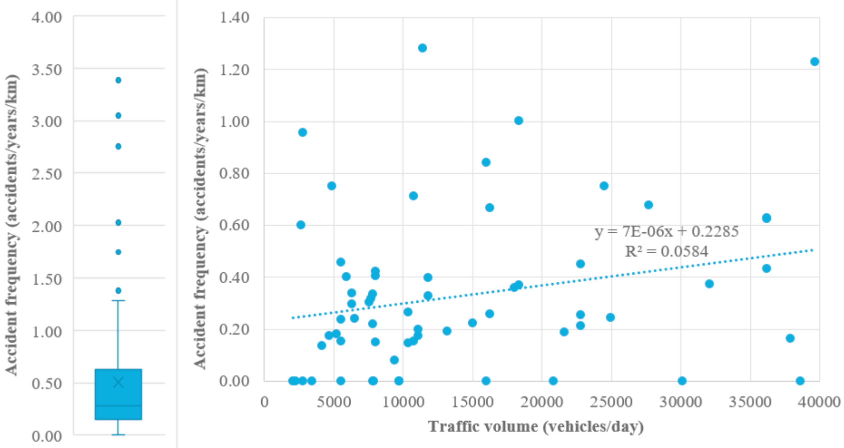

Fig. 2. Boxplot of accident frequencies and preliminary traffic volume-accident frequency relationship

3. Analysis of geometric design issues

The analysis conducted in the previous section was useful to highlight that: 1) crash rates in two-way two-lane rural road tunnels are at least comparable with crash rates on open road sections, 2) multi-vehicle accidents such as rear-end are more frequent in tunnels rather than run-off accidents, 3) accidents may cluster at the tunnel enter/exit. While the likelihood of accident occurring seems then comparable, the potential consequences of tunnel accidents could be not comparable as well. They could be dramatic and potentially leading to other evacuation-related issues (e.g. Ronchi et al., 2012). For this reason, safety-related aspects of tunnel design should be particularly looked after. In detail, the geometric road tunnel design is a crucial aspect.

On the other hand, the parallel consideration of environmental and geotechnical/structural issues necessarily lead to some trade-offs between different aspects of the rural tunnel design. Among these issues, some problems are particularly targeted in this article, since they may severely influence the road tunnel geometric design process, and the safety conditions in turn. They imply the need for locally widening the tunnel cross-section for different geometric-related reasons. However, these needs are in contrast with other needs, especially in impervious terrains. Moreover, besides of being influential in safety, these design issues were chosen since they are scarcely treated in previous research and there are no clear and detailed prescriptions to solve them in technical documents.

In detail, the three following aspects which entail the road tunnel cross-section widening on two-way two-lane rural roads are analyzed:

- Implementation of lay-bys inside road tunnels;
- Implementation of additional clearances/widening in curves due to different requirements;
- Implementation of supplementary/climbing lanes inside road tunnels.

The issues deriving from implementing the listed facilities are discussed, leading to some practical indications which may be useful for practitioners. These facilities are generally implemented worldwide. Hence, examples in this article are reconstructed with reference to particular road standards, but similar results could have been obtained by using other standards. Moreover, some trans-national guidelines are mentioned, where relevant.

3.1. Design of lay-bays

The design of lay-bys in road tunnels implies a gradual variation in the road cross-section. Due to the technical difficulties in the excavation and covering of a gradually varying cross-section, the cross-section has usually only one difference between the standard and the lay-by section, as shown in Fig. 3.

Fig. 3. (left) local widening of the tunnel cross-section in correspondence with lay-bys (with example measures taken from Italian standards). (right) solution representing the implementation of oblique vertical walls in presence of lay-bys.

However, the condition represented in Fig. 3 leads to the presence of right corners between the lateral walls of the standard section and the lateral walls in presence of lay-bys. These corners are dangerous obstacles, which should be avoided from a road safety perspective (PIARC, 2016). In fact, while accidents due to these obstacles are very rare, their occurrence may have dramatic consequences (Tesson et al., 2015). For example, in Switzerland (Sierre tunnel, 2012), a bus collided with the back wall of a lay-by leading to 28 dead passengers. Hence, some studies have provided some design indications to mitigate risk given by these obstacles (e.g. Tesson et al., 2015): a) crash cushions or barriers (steel or concrete barriers); b) preventive or additional measures such as rumble strips, road markings and lighting.

However, all measures designed to reduce risks given by lay-bys corners should guarantee an unimpeded and immediate access to evacuation facilities. The design should be based on speeds and the types of vehicles which could compose the tunnel traffic flow, in order to individuate the most likely (and dangerous) collisions. Hence, while the excavation technologies are updating, solutions are composed of geometric limitations and technical prescriptions.

For example, a possible practical solution could be represented by the implementation of an oblique vertical wall, which may follow the shape of the lay-by during the gradual variation of the road cross-section. This wall should have similar stiffness than the lateral walls of the standard cross-section. This proposed solution is represented in Fig. 3.

3.2. Design of curve widenings

The design of horizontal curves on two-way two-lane roads may imply enlargements of:

- lanes, to ensure safety margins for the encroachments of vehicles (especially if heavy) in the opposite directions;
- shoulders, to ensure sight distances coherent with the required stopping distances in presence of lateral obstacles.

In tunnel sections, the need for curve widenings (both of lanes and shoulders) then requires a varying cross-section, with respect to the standard road cross-sections. To avoid enlargements, the radii of curves should be bounded inferiorly, as a function of design speeds and the variables affecting the stopping distances calculation. The widening of shoulders is often more demanding that the lane widenings, being often related to very sharp radii (e.g. in the Italian standards for R < 225 m). Whereas, shoulder widenings for visibility reasons may be needed even for large radii.

In curves, the following conditions should be always guaranteed:

$$SSD = SSD(R, Lc, LW, SW) \geq SD \cong \frac{S(R,f_t)^2}{2g\,(f_l(S(R,f_t)) \pm i)} + S(R,f_t)\; t_{pr}(S(R,f_t)) \qquad (1)$$

Where:

SSD = Stopping Sight Distance, reported on the lane centreline starting from the tangent to the closest lateral obstacles, which can be expressed as a function of the radius of curvature R, the length of the curve L_c (if the tangent to the obstacle extends beyond the curve length as shown in Fig. 4), the lane and shoulder widths.

SD = Stopping Distance, as a function of the design speed S (depending on the radius R and the cross friction f_t), the longitudinal friction f_l, the grade i, the perception-reaction time t_{pr}, and the resistances to motion (here neglected).

In tunnels, the lateral obstacle is the lateral wall of the tunnel itself and then, the shoulder limit can be always considered for the drawing of tangents in the geometric constructions of the stopping sight distances (Fig. 4).

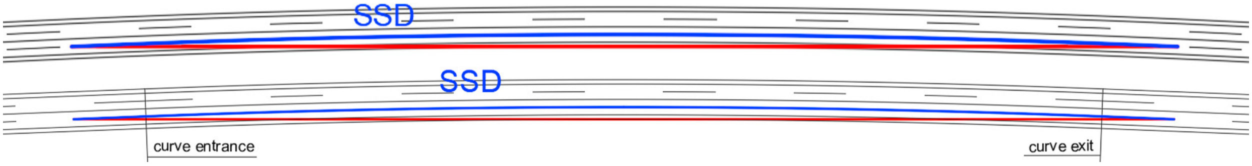

Fig. 4. (top) limiting stopping sight distance included in the curve length; (bottom) limiting stopping sight distance greater than the curve length.

Due to the large variability of all the terms included in Eq. 1, it is rather difficult to determine the minimum radius R which can always meet visibility requirements in two-way tunnels. Different values were proposed indeed, given the variability of several factors in previous studies (Bassan et al., 2016; 2017). An example of calculation is here referred to Italian standards, for different two-lane rural road cross-sections (characterized by the following widths of lanes and shoulders: 3.75 m, 1.50 m for the road category "C"; and 3.50 m, 1.00 m for the road category "F"), and for different longitudinal grades (considering prescriptions set in the EU Directive). Both the two conditions identified in Fig. 5 are explored, by prudently not considering the presence of spiral transition curves in the case: SSD > L_c.

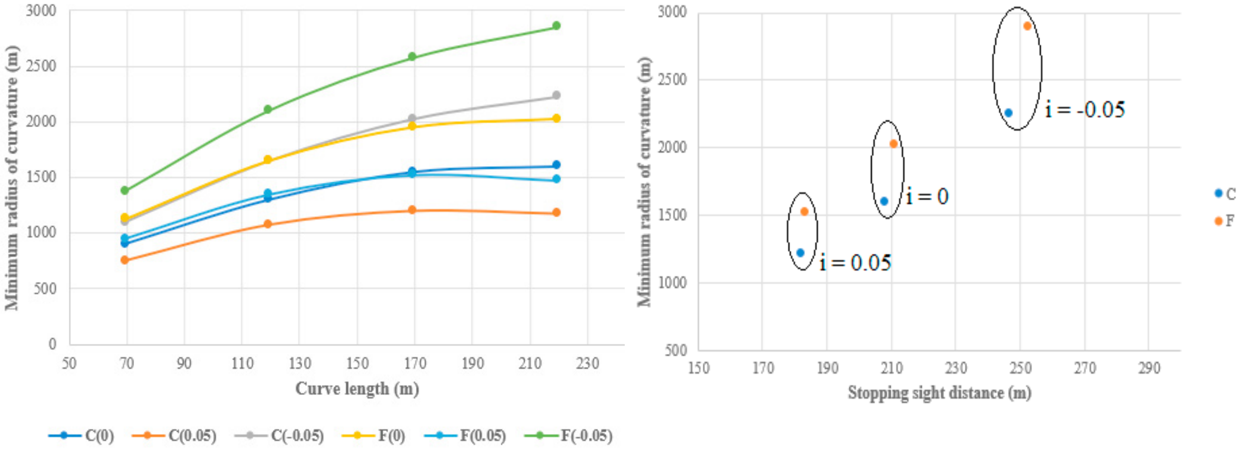

Fig. 5. minimum radius of curvature for the two road categories considered, in case of (left) stopping sight distance greater than the curve length, for different curve lengths and grades, (right) stopping sight distance included in the curve length for different grades.

In most cases, the minimum radius of curvature suggested to avoid shoulder widenings for visibility reasons is > 1000 m. Hence, it corresponds to maximum design speeds (in this case: 100 km/h). Clearly, minimum radii could be reduced if lower posted speeds are considered instead of design speeds (and dry friction coefficients instead of wet). Anyway, it is paramount that the definition of algorithms for the design of road tunnel layouts without local widenings can be varied according to the local conditions. Hence, the designer could analyze in advance all the aspects which are useful to define the geometric layout, and then approximately compute the minimum radius which is needed to avoid widenings, with respect to local standards. In this way, a "WES" design solution (Without Enlargements Solution) could be achieved, to be compared with the other solutions through cost-benefit analyses. This procedure could help in the preliminary design steps, potentially leading to decrease design and construction costs.

3.3. Design of supplementary lanes

Supplementary lanes may be required to allow overtaking on two-lane rural highways in particular conditions. A relevant presence of heavy vehicles in the flow may imply a severe decay in the levels of service, especially on steep grades. The matter is perplexed in case of particularly long tunnels with steep grades (see scheme in Fig. 6). In these conditions, there are different prescriptions and guidelines to be met altogether, listed as follows:

- the maximum gradient and its related length beyond which a supplementary lane is required/suggested;
- the need for ensuring a minimum length of road layout with overtaking manoeuvers allowed;
- the prescription/guideline to avoid significant cross-sectional variations inside tunnels.

These three aspects may be in contrast one with each other in case of a long two-way two-lane rural road tunnel. In this case, the length of the tunnel (e.g. > 3-5 km) may represent a significant part of a road layout connecting two main destinations in the area. Hence, overtaking could be needed on it, but it must be avoided in the long tunnel section. As a consequence, supplementary lanes could be a possible solution, especially if the presence of long steep grades may encourage their implementation (see e.g. Fig. 6). However, cross-sectional variation inside tunnels are discouraged (i.e. by the EU Directive, 2004). For example, they may cause merging conflicts and then possible dangerous accidents inside tunnels. Hence, the supplementary lane should ideally extend for all the tunnel length (and in both directions if grades are as in Fig. 6). This will lead to an undivided multi-lane tunnel (or to two separated one-way road tunnels with two lanes) and its construction cost could not be justified in most cases of application, if the road has not a clear strategic importance (as in most cases of two-way two-lane rural road tunnels). Moreover, the environmental and cost impact will be doubled, by implying the severe enlargement of the tunnel cross section. Hence, in those cases, the implementation of a supplmentary lane in a bi-directional road tunnel could be discouraged.

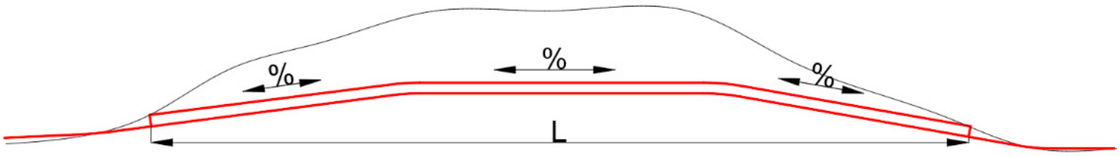

Fig. 6. scheme of elevation profile of a long two-way two-lane rural road tunnel in impervious terrain.

In parallel to the practical issues posed to the construction of a supplementary lane in tunnels, its safety impact should be assessed. While its implementation on open road sections can lead to clear safety improvements (see e.g. Schumaker et al., 2016; AASHTO, 2010) and it is generally cost-effective (Montella, 2013), the transferability of this assessment to tunnels may be questionable. In fact, on one hand, additional lanes in tunnels (in case of multi-lane one-way tunnels) were associated to an increase in accidents (Caliendo et al., 2013). On the other hand, driving behaviour in tunnels can be safer than on open road sections (see e.g. Yeung and Wong, 2014), accident rates can be lower (Lemke, 2000) and drivers may be more prone to respect overtaking restrictions (PIARC, *https://tunnels.piarc.org/en*).

These remarks lead to considering that, when implementing supplementary lanes is practically unfeasible, the driving behaviour should be guided towards respecting the overtaking restriction. This rule could be naturally accepted by drivers in tunnels, who feel the possible overtaking maneouver as more dangerous than on open road sections, since they may be more attentive in tunnel sections than outside them (Calvi and D'Amico, 2013). The overtaking restriction can be enforced by ensuring a mandatory headway between subsequent vehicles by means of traffic control and/or appropriate road markings. The headway should be determined as a function of the design/posted speed, traffic characteristics and capacity issues. Clearly, in this case, grades should be limited as much as possible.

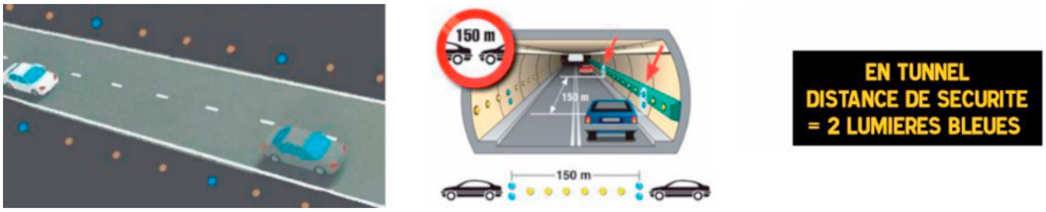

Fig. 7. Scheme of markings and signals for headways in tunnels (Frejus and Mont Blanc tunnels, taken from CETU note n.22, 2011)

4. Conclusions

The safety of road tunnels should be prioritized while making design choices, due the severe impact of potential tunnel accidents. In fact, a preliminary analysis conducted on an accident dataset related to two-way two-lane rural road tunnels has revealed that Italian tunnel crash frequencies and rates are comparable with a similar sample of open road sections. This result sheds additional light on the need for paying specific attention on two-way two-lane rural road tunnels. Differences were instead noted in the accident types (more rear-end and less run-off accidents in tunnels).

The priority for safety should be accurately followed while conducting the geometric design. However, there are some specific road geometric design issues, which are in contrast with environmental, structural and economic problems. In detail, enlarging the tunnel section (for lay-bys and curve widenings), and implementing supplementary lanes, are the main geometric issues discussed. Solutions were proposed for each of them, by considering practical needs and other constraints. In particular, in the first two cases (lay-bys and widenings), geometric reconfigurations and the implementation of a "WES" (Without Enlargement Solution) design may help in solving possible issues. In the third case (supplementary lane), the suggested solution is control-related.

Further research is surely needed, especially in the field of safety analyses of these specific tunnel sections.

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