Management of overweight vehicle traffic on road bridges

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Summary

Bridges in service in most Western Countries were built according to codes with design loads that are now inconsistent with today's traffic demands. Currently, transportation agencies do not know how to respond to transit applications on their bridges. This contribution focuses on the legal issues entailed by overweight/oversize load permits issued by transportation agencies. Indeed, correct decision-making should consider the legal liabilities involved in possible catastrophic events. In this paper we illustrate how this problem is addressed by the Department of Transportation of the Italian Autonomous Province of Trento (APT), a medium-sized agency managing approximately one thousand bridges across its territory. In their basic approach, APT does not authorize movement of overweight loads unless it is demonstrated that their effect is less than that of the nominal design load. When this condition is not satisfied, a formal evaluation is carried out in an attempt to assess a higher load rating for the bridge. If, after the reassessment, the rating is still insufficient, the bridge is classified as sub-standard and a formal evaluation of the operational risk is performed to define a priority ranking for future reinforcement or replacement.

Keywords: overweight vehicles, bridge management, multi-level assessment

1. Introduction

Managing large infrastructure systems is a multi-disciplinary activity requiring expertise from many areas, including fields of research beyond the typical scope of the structural engineer. Structural reliability is just one of many aspects affecting decisions, while economic, social, ethical and legal issues must also be considered in a risk model reflecting the owner's perspective. This contribution focuses on the legal issues entailed by the authorization - to be issued by transportation agencies - of overweight traffic on road bridges. Indeed, correct decision-making should consider the legal liabilities involved in possible catastrophic events. Currently, transportation agencies do not know how to respond to transit applications on their bridges. Because most bridges existing were built according to design code loads that are less than today's traffic demands. In this paper we illustrate how this problem is addressed by the Department of Transportation (DoT) of the Italian Autonomous Province of Trento (APT), a medium-sized agency managing approximately one thousand bridges across its territory [1].

In recent years, the APT's DoT has focused on the problems arising from the increase of the nominal load of heavy vehicles and the increasing age and deterioration of the infrastructure. A formal re-assessment of old bridges with respect to new design codes would require analysis of the original design documents, often unavailable, and structural recalculation; and very often expensive load tests. Because of the number of old bridges, an agency cannot normally carry these cost and will seek simplified approaches.

In this paper we illustrate how APT addresses the legal issues arising from the issue of transit permits by the DoT, focusing particularly on girder bridges. In the next Section we first introduce the overweight vehicle permit problem and describe how it is formally addressed in APT. Then, in Section 3, we illustrate the multi-level assessment protocol conceived to estimate the response of the bridge stock to overweight loads. The preliminary results of this analysis and an estimate of the future demand for re-assessment in APT is presented in Section 4. Some concluding remarks are made at the end of the paper.

2. APT overweight permit issue procedure

The objective of APT DoT is to provide simple, practical rules for deciding whether an overweight load permit can be issued or not, and if so, under what restrictions. In general, permits for overweight vehicles are issued by transportation agencies based on the total gross weight, the maximum axle load, the distribution of axle weights and on the axle spacing (see for example [2]). A first problem is the high variability of axle loads and spacing. A set of predefined overweight load configurations (called henceforth APT loads) is therefore defined that are more conservative than other axle combinations having the same gross weight. If a bridge is sufficient for a given APT load, it is automatically adequate for any load less than or equal to the APT load. Currently, the Italian highway code [3] places the following limits on the free movement of vehicles: maximum total weight 44 tons (440 kN); maximum axle load 13 tons (130 kN); minimum axle spacing 1.3 m. APT requires that these axle weight and spacing limits must be respected for extra-legal vehicles, whatever their gross weight. Therefore, the APT load model reproduces a multi-axle load in the most unfavorable configuration: a set of 130kN concentrated loads spaced at 1.3 m, applied on a 3.0 m wide lane. Similarly to the provisions of the 1990 Italian design code for bridges [4], the overweight vehicle model is applied in conjunction with a uniformly distributed load of 30kN m^{-1}, 6 m ahead of the first axle and 6 m behind the last axles.

Permits for extra-legal loads can be issued for unrestricted or restricted travel. In general movement restrictions can concern the presence of other traffic, the vehicle speed and time of passage. Speed limits are sometime applied by transportation agencies and nominally justified by assuming that a higher speed entails a higher dynamic response coefficient. The literature [5,6,7,8] shows that speed affects the bridge response but not necessarily proportionally. The response also depends on other factors such as span length, road surface irregularity and deck stiffness. In general there is no evidence that reducing speed reduces the dynamic response, and under certain conditions a lower speed causes higher stress on the bridge. Based on these observations APT DoT decided to disregard speed restrictions, and to define the following two load travel conditions for permit issue:

1. Free travel: the vehicle can travel freely with no traffic restriction – but restrictions on time and number of trips may apply;

2. Travel with traffic restriction: the road is closed to free traffic and the vehicle is required to cross the bridge at the center of the roadway.

Having defined the overweight load models and the travel conditions, the next step is to define an assessment procedure for the capacity of single bridges.

3. Criteria for re-assessing bridges for overweight loads

In principle, assessing a bridge to any of the APT load models and travel conditions would require full formal re-evaluation of its capacity, carried out by a professional engineer. In practice, direct re-assessment of the 1000 bridges in the territory is a very expensive task, and in many cases unnecessary. To address the cost issue, the APT approach is to estimate the capacity of the stock, using simplified and conservative approach first, then refining the analysis only if a higher load rating is required. The assessment procedure includes various simplified levels of refinement, from Level 0 to Level 3, as summarized in Table 1. All the methods are based on the following principle:

The bridge is rated for an overweight load if it is demonstrated, even conservatively, that the overweight load does not cause effects that are more severe than the original bridge design code loading.

In practice the procedure aims to demonstrate that the new overweight load condition is not worse than the most critical load condition associated with the original design assumption or as-built situation, and therefore the overweight load does not reduce the original design safety level. It is believed that this principle protects APT against legal liabilities in the case of a failure, because, following this principle APT authorizes travel only of those vehicles whose effects are less than those expected under the design assumptions.

Table 1: Level of refinement of bridge assessment under overweight loads

Assessment Level	Capacity Models	Calculation Models
Level 0	Bridge is assumed verified with no overstrength	Statically determinate condition is assumed
Level 1	As per design	As per design
Level 2		Refined model; load redistribution is allowed, provided that the ductility requirements are fulfilled.
Level 3	Material properties can be updated based on in-situ testing and observations	

3.1 Level 0

Level zero assessment is an conservative estimate of the bridge capacity based on knowing its geometry and the design code it was originally designed to. The analysis is carried out assuming that the bridge was built exactly to the nominal design load (in other words, with no overstrength), thus the bridge is automatically rated for the overweight load if it can be demonstrated that the stresses it creates are everywhere lower than or equal to those considered at the design stage.

The APT approach: 1) replaces the original design lane load with the APT load; and 2) evaluates the difference in demand between the new and old loadings. If the stress under the APT load is lower than the design load stress, it is logical to infer that the bridge is able to withstand the APT load. For girder bridges, shear and bending moment in the deck are assessed.

This analysis is simple for the free travel condition. In this case the design situation is compared to a load condition where one loaded lane is replaced with the APT load. Since the dead load is the same for both loadings, it effects are irrelevant to the evaluation and can be disregarded. Similarly, the effects of live loads outside the lane replaced are identical in the two situations, so these live loads can be disregarded too. For similar reasons the comparison is conducted using the nominal load value, disregarding any partial factors or dynamic coefficients considered at the design stage. Finally, when the original design load produces static stresses higher than the new overweight in a simply supported span, the design stresses will be higher with a statically indeterminate boundary condition. This is to say that the static scheme , whether continuous or simply supported, is also irrelevant to the comparison, so a simply supported condition can always be assumed.

In conclusion, in a case of free travel of an overweight load, the assessment is made by comparing the effects of the original design and APT loads on a single lane simply supported beam. The only parameters that control the assessment are the span length L and the design code adopted by the designer, which in turn is related to the date of construction of the bridge.

In a case of restricted travel, the effects from the original traffic lanes must be compared to the single lane APT load applied at the center of the carriageway. In this case, to compare effects, we must take account of the transverse load redistribution between the various girders using, for example, the Massonnet-Guyon-Bares theory [9].

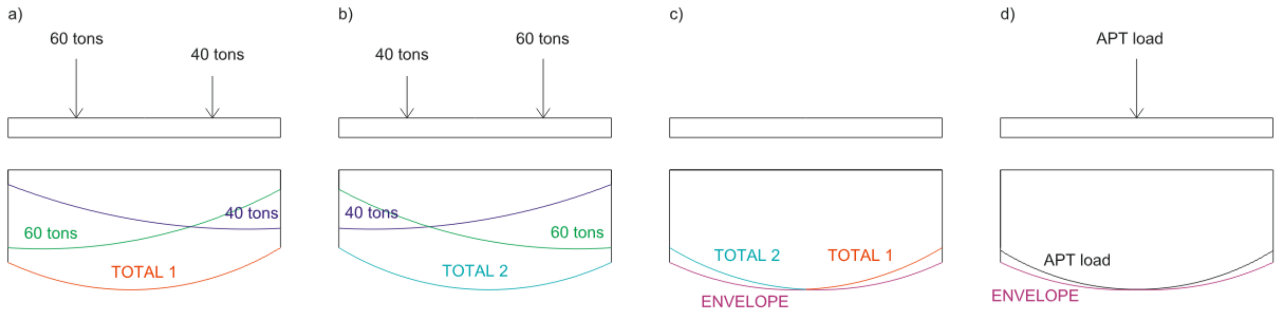


Fig. 1: a) Massonnet-Guyon-Bares coefficients multiplied by the relative load, first load design condition b) second load design condition, c) envelope of design condition, d) comparison with the effect of an APT overweight load.

Fig. 1 illustrates the procedure for determining whether the effect of the overweight load centered on the carriageway is more or less critical than any combination of design lane loads. Fig. 1a shows the cross section of the bridge deck loaded with a two-lane design condition, with the Massonnet-Guyon-Bares transversal distribution coefficients multiplied by the corresponding load highlighted. The effect of the second design load configuration is illustrated in Fig. 1b, while Fig 1c shows the envelope of design conditions. The maximum allowable APT load, applied at the center of the carriageway, is that having effects less than or equal to the envelope of the design load effects (Fig. 1d). Therefore, knowing the transverse distribution coefficients of the design load, the maximum allowable APT load at the center of the carriageway can be determined for any deck width or any bridge.

In summary, in the case of restricted traffic, level 0 assessment requires knowledge of: the Massonnet-Guyon-Bares coefficients for the bridge deck; the span length; the design code.

3.2 Levels 1, 2 and 3

The basic assumption in Level 0 assessment is that the bridge was built with no shear or moment overstrength at any section of the deck: this assumption is extremely conservative and normally not realistic. Bridge members are normally slightly oversized and very often the designer assumes conservative capacity models. In addition the mechanical properties of the materials in the as-built situation could be better than those specified by the designer. When a bridge is not sufficient from Level 0 assessment, the assessment proceeds to a higher level of refinement and is carried out by a professional engineer based on analysis of the available design documentation.

At Level 1 the evaluator is required examine the design documents to verify whether the critical structural members are oversized. This level of assessment is based only on analysis of the existing documents, without revising assumed material properties or calculation model.

At Level 2 the evaluator reassesses the bridge capacity using more refined models than those used by the original designer. Often, a capacity increase is achieved by considering inelastic behavior and spatial stress redistribution.

At Level 3 the evaluator can update the characteristic values of the variables used in the assessment, based on the results of material testing and observations. The procedure leaves the evaluator free to test the materials, without specifying the minimum number of samples or the type of test. However, if the evaluator wants to use the test results quantitatively, a Bayesian probabilistic update technique should be applied. This can be done even if the design documentation is not available: in this case, an accurate survey of bridge geometry and extensive material sampling are needed.

3.3 Lack of capacity of substandard bridges

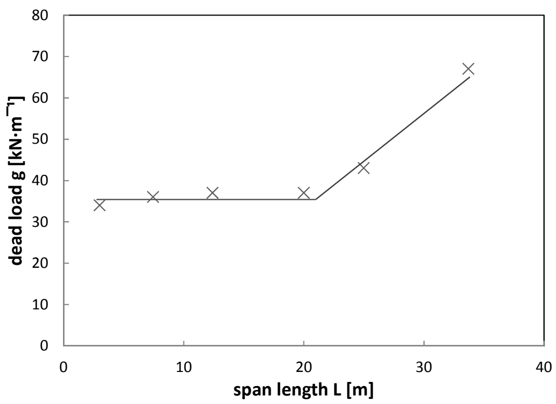
To classify substandard bridges, we need to quantify the extent of their deficiency. A useful index here is the *critical live load multiplier* η, defined as the ratio between the stresses caused by the APT load and those due to the design load. For girder bridges there will be critical load multiplier for bending moment and shear stress, and these indices are calculated at each section of the span.

A critical live load multiplier η less than 1.0 can have differing impact on the overall safety of the bridge, depending on the magnitude of the dead load. For example, a live load multiplier of 0.90 could be critical for short span steel girder bridges, where the live load is dominant, but is likely to be much less critical for a long span reinforced concrete bridge, where the dead load dominates.

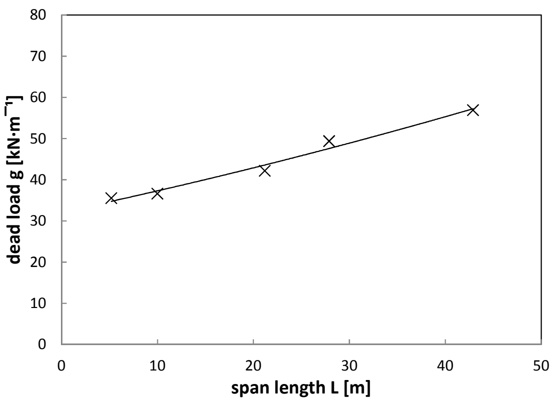
An index that better reflects bridge understrength with respect to the overweight load is the *lack of capacity factor* α, defined as the percentage of additional capacity ΔR needed to safety carry the overweight load. For girder bridges this coefficient indicates how much the most critical bending moment or shear stress must increase for positive verification of the bridge. There is a direct relationship between indices α and η. If R is the capacity of the bridge at a specific limit state and S is the overweight load demand, the lack in capacity α of the bridge can be expressed as follows:

$$\alpha = \frac{\Delta R}{R} = \frac{S-R}{R} = \frac{G/Q+\eta-(G/Q+1)}{G/Q+1} = \frac{\eta-1}{G/Q+1} \tag{1}$$

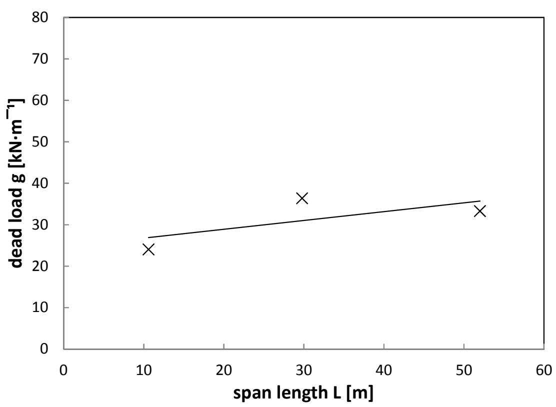
where G is the effect of the dead load and Q is the effect of the live load. Equation 1 shows that computing index α requires knowledge of the G/Q ratio for the bridge, and this in turn depends on the bridge characteristics as included in the design documentation: normally not known for a Level 0 assessment. To estimate index α at Level 0, a practical solution is to provide approximate expressions for the dead loads of various bridge structures and span lengths. The graphs in Fig. 2 show the dead load of a 3 m wide lane calculated for a sample of bridges of differing construction technologies, with proposed fitting curves that can be used to estimate the dead load once the bridge span is known.



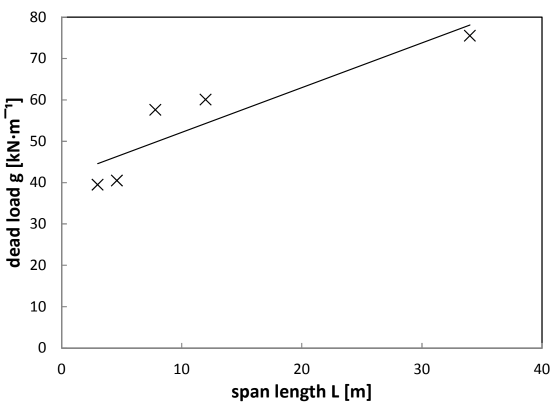
a) reinforced concrete girder



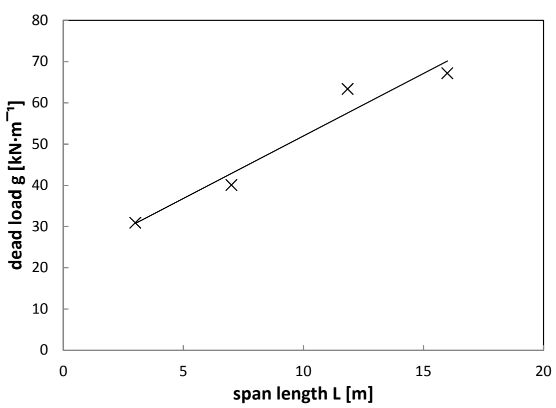
b) precast reinforced concrete girder



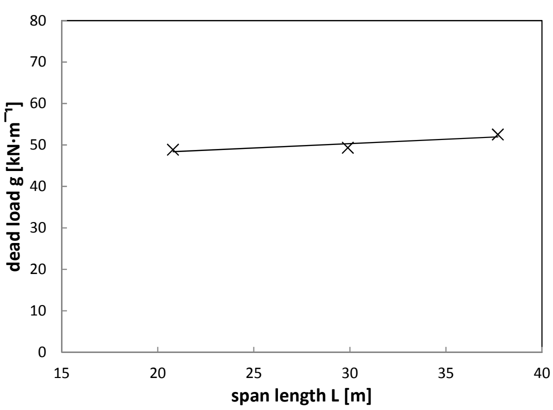
c) steel girder



d) reinforced concrete slab



e) precast reinforced concrete slab



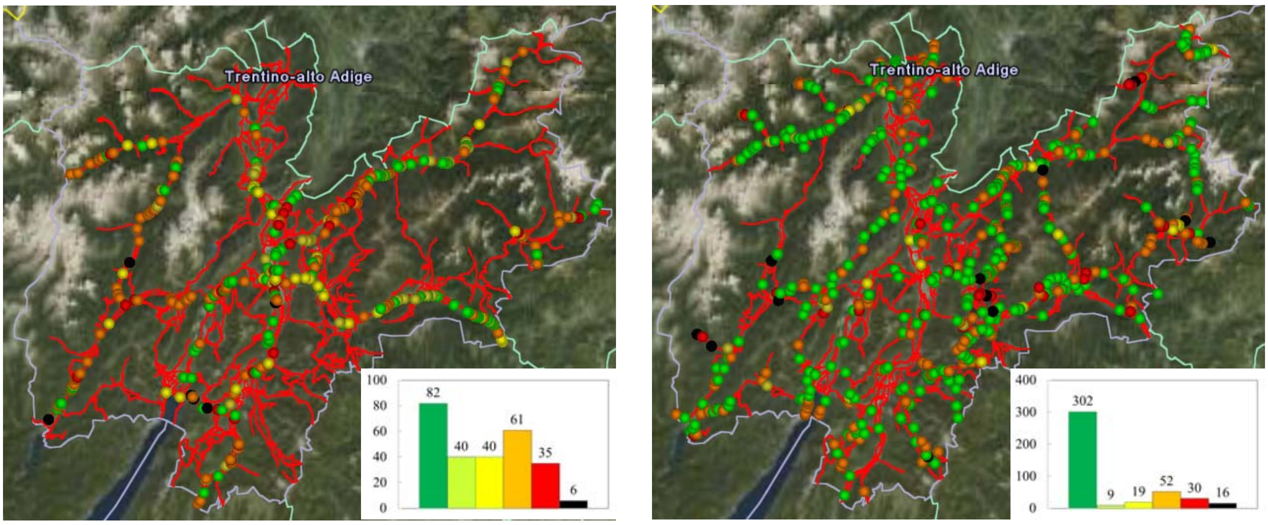
f) reinforced concrete box girder

Fig. 2: Bridge span to dead load relationship for various bridge technologies: experimental samples and fitting curves.

4. Level 0 analysis results and demand for re-assessment

APT has defined a ten-year objective to assess/retrofit its bridge stock to allow free or restricted travel of minimum overweight load vehicles over the entire network. In particular, the road system has been defined as two networks: strategic and non-strategic. The strategic network includes all inter-regional highway links, with 574 km of highways, 264 girder bridges and 87 arch bridges; the non-strategic network is the remaining 1836 km of local road links, including 428 girder bridges and 174 arch bridges.

The mid-term objective for the strategic network is to allow free travel of 6-axle overweight vehicles with maximum axle weight of 12 tons (120 kN) and total weight 72 tons (720 kN), and restricted travel of 8-axle overweight vehicles with maximum axle weight of 13 tons (130 kN) and total weight of 104 tons (1040 kN). Similarly, for non-strategic bridges, the targets are free travel of any 56 ton vehicles and restricted travel of 72 ton vehicles.



a) strategic road network b) non strategic road network

Fig. 3: deficiencies for target APT load models on strategic and non-strategic networks

Fig. 3 shows the results of Level 0 assessment using the desired overweight loads for the strategic and non-strategic networks limited to girder bridges. In the map each dot corresponds to one bridge location, while the dot color encodes the assessment result in terms of the index α with the following meanings:

- dark green: the bridge is acceptable at level 0 and does not require further assessment;
- light green: the bridge is not acceptable at level 0, with a lack in capacity $\alpha \leq 4\%$, however α is acceptably small and no further assessment is required;
- yellow: the lack of capacity is $4\% < \alpha \leq 8\%$; the bridge has an estimated 50% chance of being acceptable after Level 1 evaluation;
- orange: the lack of capacity is $8\% < \alpha \leq 14\%$; the bridge has an estimated 50% chance of being acceptable after Level 2 evaluation;
- red: the lack of capacity is $14\% < \alpha \leq 47\%$; the bridge has an estimated 90% chance of being acceptable after Level 3 evaluation;
- black: the lack of capacity is $\alpha > 47\%$; the bridge has an estimated chance less than 10% of being acceptable even after Level 3 evaluation; so full formal re-assessment is needed with possible retrofit strengthening.

We note that for non-strategic roads, 311 of 428 girder bridges are automatically accepted, while for the strategic network only 122 of 264 bridges pass the Level 0 analysis. To cope with the re-assessment objective, the APT DoT has developed a plan for re-assessing substandard bridges. Fig.4

outlines the decision-making scheme and shows the prediction of re-assessment results for strategic bridges. More specifically, after Level 0 analysis, 122 bridges are automatically assessed, while another 6 are unlikely to pass any further level of simplified assessment, so must be formally reassessed and possibly be strengthened. Of the remaining 136 bridges, 89 have no design documents, so must be directly assessed under a Level 3 procedure. The other 47 bridges, with design documents, can undergo the multi-level assessment procedure. After reassessment, APT estimates there will be 27 substandard bridges out of the 264 total. These bridges will be analyzed individually and possibly strengthened to resist higher loads.

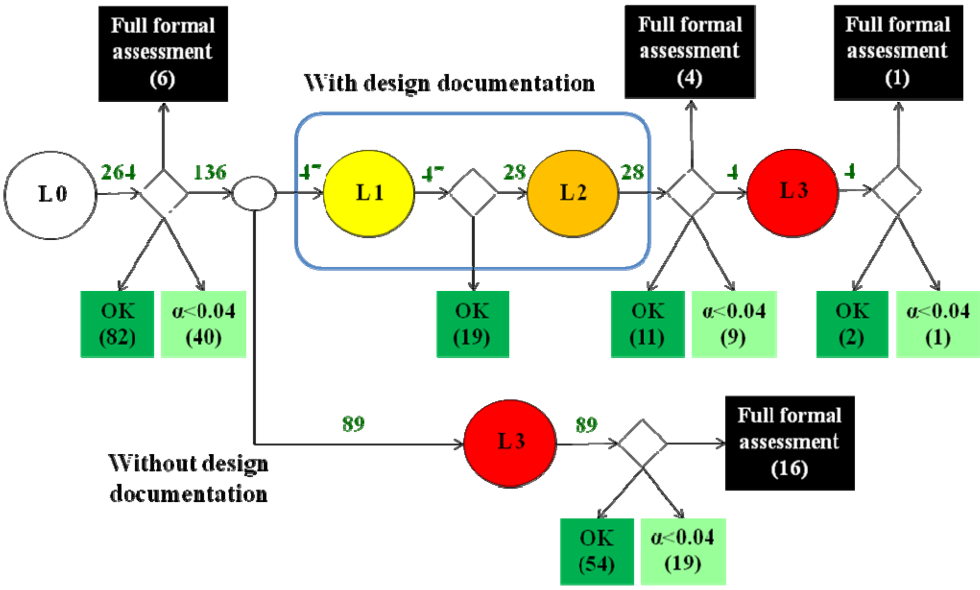


Fig. 4: anticipated results of re-assessment for strategic girder bridges.

5. Conclusions

In this paper we illustrate how the problem of overweight traffic management is addressed by the DoT of the Italian Autonomous Province of Trento (APT). More specifically, APT has defined practical criteria for issuing overweight load permits, based on the definition of a number of reference load models and on two travel conditions (free and restricted traffic). The mid-term APT objective is to assess in the next 10 years: the strategic road network for 72 ton free travel vehicles, and 104 ton restricted travel vehicles; the non-strategic network for 56 ton free travel vehicles, and 72 ton restricted travel vehicles. APT has also defined a protocol for reassessing existing bridges using a multi-level verification procedure. Based on Level 0 analysis, of the 692 girder bridge in the stock, 433 are automatically acceptable, while 259 (142 of which are strategic) need further re-assessment before being formally acceptable. To re-assess substandard strategic bridges, APT has launched a re-assessment program, expecting to find about 27 substandard bridges that need retrofit strengthening.

Acknowledgements

This research was made possible thanks to the financial support of the Department of Public Works of the Autonomous Province of Trento: Stefano De Vigili, Luciano Martorano, Guido Benedetti, Paolo Nicolussi Paolaz and Matteo Pravda are particularly acknowledged. The authors also wish to thank Alessandro Lastei, Luca Mattiuzzi, Alessandro Lanaro and Francesca Bortot, all collaborating in the research group at the University of Trento, for their contribution to the development of this project.

References

[1] ZONTA D., ZANDONINI R., and BORTOT F., "A reliability-based bridge management concept". *Structure and Infrastructure Engineering*, Vol, 3, No. 3, 2007, p.215-235.

[2] Federal Highway Administration, "Oversize/Overweight Load Permits", http://ops.fhwa.dot.gov/freight/sw/permit_report, assessed 30 Oct. 2012.

[3] MINISTERO DELLE INFRASTRUTTURE E DEI TRASPORTI, "Nuovo codice della strada", *D.L. 30 aprile 1992 n.285 e successive modificazioni, Gazzetta Ufficiale della Repubblica Italiana, n. 114 ,18 maggio 1992.*

[4] MINISTERO DEI LAVORI PUBBLICI, "Aggiornamento delle norme tecniche per la progettazione, la esecuzione e il collaudo dei ponti stradali", *D.M. 4 maggio 1990*, *Gazzetta Ufficiale della Repubblica Italiana, n.24 – Serie Generale - 29 gennaio 1991.*

[5] CANTIENI R., "Dynamic Load Tests on Highway Bridges in Switzerland - 60 Years Experience of EMPA", *EMPA Report No. 211*, Swiss Federal Laboratories for Materials Testing and Research, Dübendorf, Switzerland, 1983.

[6] PAULTRE P., CHAALLAL O., and PROULX J., "Bridge dynamic and dynamic amplification factor – a review of analytical and experimental findings", *Canadian Journal of Civil Engineering*, No.19, 1992, pp. 260-278.

[7] BRADY S.P., OBRIEN E.J., and ZNIDARIC A., "The effect of vehicle velocity on the dynamic amplification of a vehicle crossing a simply supported bridge*", Journal of Bridge Engineering*, Vol. 11, Issue 2, 2006, pp. 241-249.

[8] SENTHILVASAN J., THAMBIRATNAM D.P., and BRAMELD G.H., "Dynamic response of a curved bridge under moving truck load", Engineering Structures, Vol. 24, 2002, pp. 1283-1293.

[9] MASSONNET C., and BARES R., "Analysis of beam grids and orthotropic plates by the Guyon-Massonnet-Bareš method", London, *Lockwood*; Prague, *SNTL*, 1968.