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An Italian road pavement design method for bus lanes: proposal and application to case studies

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Abstract

In urban centres, the presence of bus lanes is essential to facilitate public transport services for a better sustainability of the cities and reduction of private traffic and pollution. However, bus lanes need a specific geometric (i.e. road layout) and structural (i.e. pavement layer thickness) suitable design. The pavement design of bus lanes in urban areas is often performed using traditional methods, already used for other types of roads. Given the geometric and structural peculiarities of each road in the urban centres due to the historical city development, the application of these methods can lead to an incorrect road pavement design.

For this purpose, a first attempt of a road pavement design system has been developed for bus lanes: it is a specific catalogue proposal for this type of lanes, which can support the technicians in evaluating the most appropriate solutions in terms of materials and thickness, for both new construction and maintenance.

After evaluating the types and main characteristics of buses circulating in Italy, traffic levels (in terms of equivalent standard axle loads), subgrade bearing capacity and pavement structure were hypothesized. Assuming three possible structures and five traffic levels, a total of forty-four design solutions were drawn up. The required pavement thickness varies from 17 to 47 cm for a new lane construction and from 9 to 22 cm for an existing lane maintenance.

All the proposed solutions have been verified by methods and models based on multi-layer elastic theory available in the literature. Moreover, their validity was evaluated applying the solutions to real cases. The results of this work encouraged the authors to improve the catalogue inserting solutions with natural stone, particularly used in historic centres for architectural and aesthetical reasons, and to differentiate the pavement thickness of bus lanes subject to high stresses (intersections, stops, etc.).

Keywords: bus lane; road pavement; pavement design; catalogue; construction; maintenance

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1. Introduction

In cities, especially in Italian historic centers, the lanes are often reserved for collective means of transport (so called "bus") mainly to reduce the number of vehicles circulating in the city center for loss of space in the cities and pollution reasons. The Italian Road Code (legislative decree 30 April 1992 n.285 and subsequent amendments) and the D.M. 05/11/2001 report the definition of "*reserved lane*", i.e., a "lane intended for the exclusive circulation of one or some categories of vehicles". In some cases, the entire road may be completely reserved for the exclusive circulation of the buses. These two standards indicate the dimensions of the reserved lanes and their possible arrangement in different contexts (two-way or one-way lanes). In this paper, the Authors refer principally to the bus lanes. In Italy, the minimum width of the bus lane is equal to 3.50 m. The separation between the reserved lanes and the rest of the carriageway takes place with horizontal markings (a yellow strip of 30 cm flanked by a white strip of 12 cm), physical separators (rubber or concrete curbs, traffic dividers), sidewalks, railings, hedges or safety barriers (more expensive and durable, but effective against lane invasion). In Italy, the horizontal signs are generally used for the separation between lanes. The physical separators are indeed used for transport system circulating in a reserved lane with a high degree of protection, guaranteeing a transport service with greater speed and frequency, that is called "Bus Rapid Transit" (BRT) (APTA, 2010).

Traditionally, in a road the reserved lane has a pavement thickness equal to that of the other lanes. In general, a flexible pavement consisting of a series of asphalt layers (wearing, binder and base courses) and a foundation layer is designed. The number of layers and their thicknesses depend on the design vehicles number, as well as of maintenance interventions that are carried out. Really, the standard structure is often simplified both for new-constructed pavements (laying only wearing, binder and foundation courses) and those subjected to maintenance (laying of superficial layers, rather than the complete rebuilt, is commonly preferred). However, the greater gross vehicle weight of the buses allowed to circulate on the reserved lanes causes premature pavement deterioration. This happens also in historic centers, where pavements have surface layer built with stone elements (i.e., cobblestones). The lack of an adequate design of the pavement thicknesses, not connected with the real weight and with the dynamic forces involved, often leads to the premature pavement failure, and subsequent maintenance burdens for roads owner (usually the Municipalities).

Literature reports only several works about the construction of bus lanes. Tsai et al. (2010) evaluated the use of reinforced concrete for paving the lanes reserved for BRT service, with concentrated and repetitive loads very different from those found in modern Italian cities. Ebels (2016) described some examples of different pavement types (flexible and rigid) for reserved lanes in South Africa, reporting practical considerations, benefits and limitations. Many authors indicated concrete as the appropriate material for the BRT service, also showing the potentiality of bituminous mixtures for bus lanes (LoTAG & LoTAMB, 2013). Other studies focused on the relationship between bus accidents and various external factors, including pavement and its surface characteristics. Nguyen et al. (2021) defined a Bus Ride Index (BRI) for flexible pavement, underlining the adequacy of the BRI in estimating the ride comfort of different vehicles in relation with International Roughness Index (IRI).

Given the limited literature in the sector, the Authors evaluated various design solutions for reserved-lanes road pavement dedicated to urban and suburban bus service. Such lanes are affected by a vehicular traffic and speed different from that of a classic urban road lane. Except for a few authorized categories (e.g., taxi), the traffic spectrum varies in relation to the different types of buses. In particular, the objective is the definition of a catalogue proposal, specifically reserved for this type of intervention, supporting the technician into the evaluation of the appropriate solution in terms of materials and layer thicknesses, both in the case of lane new construction or maintenance. With this purpose, the road materials and their performance were evaluated. Calculation methods were identified to design the solutions in the catalogue, verifying each solution hypothesized for the different service levels and boundary conditions. With respect to the existing Italian catalogue (CNR, 1995), this allowed to account for new vehicles characteristics, pavement materials and failure models, also proposing solutions for maintenance operations.

2. Methods

As indicated in Figure 1, the research workflow consisted of the following steps: 1) collection of the information on most-utilized vehicles inside reserved lanes (i.e. the buses) and evaluation of the equivalent axles; 2) identification of materials to be used for new construction and maintenance and definition of climatic data (Italy is the reference Country); 3) definition of pavement failure models (low-temperature and fatigue cracking, rutting); 4) first draft of the catalogue, defining the pavement configurations and their layers (both for new construction and maintenance); 4) definition of the most suitable design method for the catalogue delineation purpose; 5) construction of the structural model and stress-strain analysis for the road pavement configurations; 6) validation of the catalogue by checking the pavement response to the design loads and comparing the results with those of the failure models; 7) proposal of final pavement catalogue (both for new construction and maintenance).

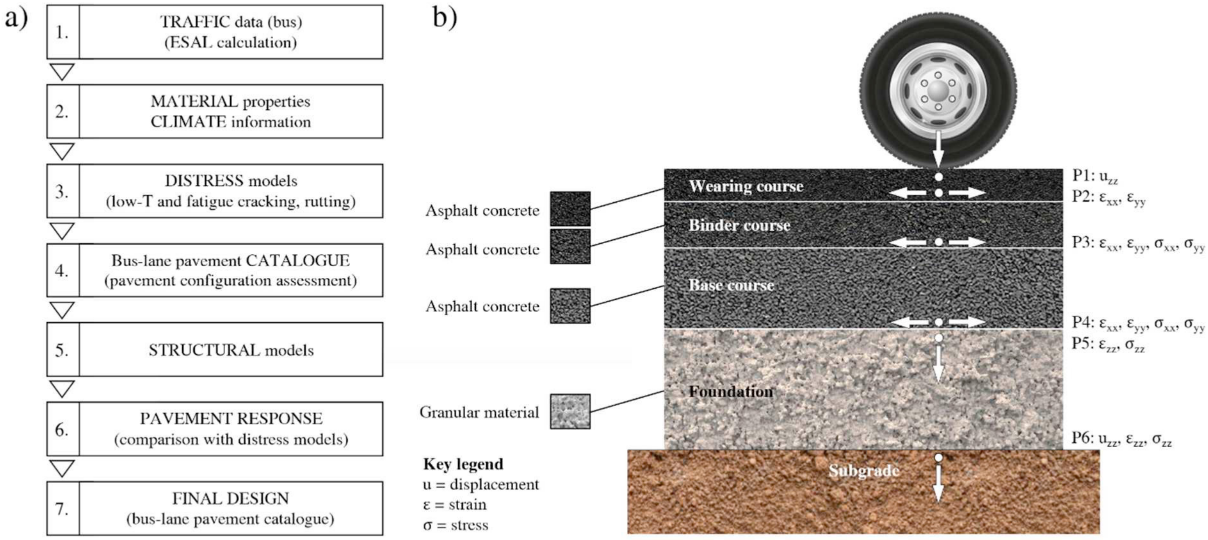

Fig. 1. (a) Workflow at the base of the catalogue definition; (b) scheme of road pavement and stress-strain response.

The first step regarded the evaluation of the main characteristics of the vehicles mostly utilized by the Italian urban transport companies (i.e., bus length and axle loads)). Values of axle loads were transformed into equivalent axles by means of equivalent axle load factor (EALF) coefficients defined below, allowing the definition of reference traffic values (standard equivalent axle) and the different service levels of traffic. These were used to design the solutions proposed in the catalogue.

The catalogue structures were proposed based on: the type of work (new construction or maintenance), the bearing capacity of the subgrade or the existing layer/s, the level of service and the climatic conditions of the design area (Italy). Together with traditional paving materials (bituminous mixtures for wearing, binder and base courses, cement bound mixtures for foundation), high-performance materials such as high-modulus asphalt concrete or asphalt rubber were also included, despite their higher costs, to promote the pavement structural resistance The average Italian climatic conditions were considered in this work. The reference parameters (temperatures, daytime thermal excursions, average solar radiation and monthly wind speed) were obtained from the Italian Pavement Catalogue (CNR, 1995).

The vehicles for public transport service using the reserved lanes have significant impacts on road pavements, similarly to the transit of heavy vehicles. In this study, the Authors considered the vehicles' effects on road pavements by evaluating the following distresses: rutting, pavement surface corrugation and shoving (at the intersections or at the sharp planimetric curves), other issues related to concentrated loads in small areas (at the intersections or at the stops or at the parking areas), fatigue cracking due to repeated loads and thermal cracking. With formulas and theoretical models, the Authors used the hypothesized traffic values to calculate whether these lead to an early deterioration of the road pavement solutions proposed in the catalogue.

The "Guide for Design of Pavement Structure" developed by the American Association of State Highway and Transportation Officials (AASHTO, 1986-1993) was used as design method for the road pavement solutions defined in the catalogue. These solutions for reserved lanes were validated with empirical-mechanistic (rational) methods and structural response calculation models (using the Boussinesq elastic theory). Using control points within the road pavement structure (as indicated in Fig. 1 (b)), the effects of the loads on the pavement were evaluated by comparing the modeled value with the typical resistance given by the selected pavement layers.

3. Catalogue proposal and validation

Starting from the traffic levels, a catalogue proposal was shaped in two sheets, the one related to new construction and the other for the maintenance. Depending on the traffic category and the characteristics of the supporting structure (the subgrade in new-constructed pavements, the non-milled layers in the case of maintenance), the resulting pavement thicknesses were indicated in two catalogue sheets. By simulating the passage of the equivalent axles estimated in the design phase, the stress-strain state of the various structures was calculated to verify a pavement lifetime, with particular reference to degradation phenomena.

3.1. Bus traffic

The movement of a vehicle on a multilayer pavement generates stresses, displacements and strains on the surface and within the pavement (Fig. 1 (b)). The stress-strain state is downward transmitted to underlying layers and subgrade with different values point to point. The repeated application of a load significantly affects the physical characteristics of the pavement during its lifetime, generating a progressive decay until to its failure. Therefore, the extent and number of load repetitions and strains affect the pavement in terms of performance and durability (Fwa, 2006, Huang 2004, Yoder and Witzack, 1975).

To identify the stresses affecting the bus lane pavement it is necessary to study the characteristics of the design vehicles. The Italian law (Road Code) establishes the legal permissible maximum weight. It must not exceed: 1) 19 tons for two-axle buses or trolleybuses for public services in urban or suburban lines; 2) 30 tons in the case of a three-axles articulated bus; 3) 12 tons on the most loaded axle. Taken these limits as a precautionary measure, the characteristics of the circulating vehicles, and those available on the market, were evaluated (next-future available vehicles were also considered). The distinction between urban and suburban vehicles was not considered because of the technical similarity of the two categories (vehicle preparation and the number of access doors only vary). Based on the technical data sheets of the manufacturers, the following vehicles' weights were collected: gross vehicle, empty, front axle, central axle (if present), rear axle (driving axle). The length and wheelbase of axles of the different vehicles were evaluated, grouping quite similar configurations in representative values. It was hypothesized that methane (CNG), hybrid fuel-cell (hydrogen) and, above all, electric traction will represent the largest part of circulating vehicles in the near future. All such vehicle types generally possess higher empty weights and loads if compared to those with other traction types. Vehicles with length of 15 m were not included in the catalogue because no longer marketed (they were accounted as 18 m-long vehicles). Vehicles with a length of 24 meters were not considered, although currently used in some European countries such as France, (given the complexity of urban road layouts, they are not allowed to circulate in Italy). The design vehicle's data are reported in the Tab. 1.

Table 1. Data of the buses used to design the proposed pavement catalogue.

Bus length [m]	Axle weight (empty / full load) [t]			Maximum allowable weight [t]	Axle number [-]	Axle weight for 75 % load factor [kN]			EALF single passage
	Front	Central	Engine			Front	Central	Engine	
< 10.0	2.5 / 4.0	-	4.0 / 8.0	12	2	35	-	70	0.62
10.0 – 11.5	2.5 / 4.0	-	5.0 / 10.0	15	2	45	-	90	1.70
11.5 – 13.0	3.0 / 7.5	-	7.5 / 11.5	19	2	35	-	105	3.00
14.5 – 18.0	3.0 / 7.5	7.5 / 11.0	7.5 / 11.5	30	3	60	100	100	5.20

The Authors assumed an average vehicle load factor per day equal to 75%, since the buses reach a load factor of 100% only for few hours in a day, having a lower load factor for the remaining hours in the day. The estimate of a load factor of 100% would involve a pavement oversizing effect with higher (construction or maintenance) costs. All vehicles were supposed to mount the same type of tires (275/70 R22.5) to simulate the footprint on the pavement surface, considering a typical inflation pressure of 0.55 MPa.

The pavement design referred to the number of passages of equivalent twin wheels axles of 80 kN (ETWA80) using EALF coefficients in the transition from real axles to standard ones. According to Yoder and Witzack (1975), for the calculation of these coefficients, Eq. 1 was used linking the weight of the real axle L_x (in kN) with the weight of the equivalent axle (in kN):

$$EALF = \left(\frac{L_x}{80}\right)^4 \tag{1}$$

Once calculated the EALF coefficients for each vehicle (Tab. 1), the equivalent twin wheels axles of 80 kN (ETWA80) were calculated through Eq. 2, defining the traffic levels of design.

$$ETWA80_x = \left\{[(f \cdot a_x) + (pf \cdot b_x) + (F \cdot c_x) \cdot C_d] \cdot \left[\frac{(1+r)^n - 1}{r}\right]\right\} \cdot n \tag{2}$$

where:

- the subscript x denotes three cases for different public transport service: x = 1 is the service with summer ride reduction ($a_1 = 245$, $b_1 = 60$, $c_1 = 60$), x = 2 is the service with summer ride reduction using pre-holiday timetable during the weekdays in summer months ($a_2 = 200$, $b_2 = 105$, $c_2 = 60$), x = 3 is the service with seasonal variation (summer/winter) of three months ($a_3 = 64$, $b_3 = 13$, $c_3 = 13$);
- f, pf and F are the EALF value (Tab. 1) multiplied by the passage number per day for weekdays, pre-holidays and holidays, respectively;
- C_d is the transversal variability of the vehicle trajectory within the lane that depends mainly on the lane width (varying from 3.50 m to greater than 4.30 m);
- n is the lifetime of road pavement, equal to 15 years for the present catalogue design;
- r is the predicted annual growth rate of the traffic (1%), in percentage.

The pavement solutions were designed by fixing five traffic levels in terms of ETWA80 passes (Tab. 2).

Table 2. Traffic levels.

Traffic levels	ETWA80 passes
1	300,000
2	600,000
3	1,500,000
4	3,000,000
5	6,000,000

3.2. Materials hypothesis

In the case of new construction (or re-construction), three possible values of the subgrade bearing capacity were assumed: M_r = 30 MPa (CBR = 2%), 90 MPa (13%) and 150 MPa (28%). Values were expressed both in terms of resilient modulus M_r (as for the standard Italian catalogue) (CNR, 1995) and as CBR, i.e., one of the most diffused parameters for soil bearing capacity (Pasetto et al. 2018). In case of maintenance, a single value for the subgrade bearing capacity, equal to 150 MPa (28%), was supposed in view of the probable high compaction level given by the existing pavement structure. It was also considered that a variable thickness remained above the subgrade, corresponding to the portion of existing bituminous mixture that was not damaged and subsequently milled. Then, three values of stiffness modulus E (T = 25 °C) were attributed to existing layer, depending on the quality assumed for its material: 2,000 MPa, 3,000 MPa and 4,000 MPa.

Tab. 3 summarizes the materials, also giving the layer coefficients a_i requested to design the structures through the AASHTO Method (AASHTO, 1986-1993).

Table 3. Materials, layers, coefficients and stiffness to design the catalogue pavement solutions.

Materials	Pavement layer	a_i coefficient [-]	Stiffness E [MPa]
Asphalt concrete (AC)	Wearing course	0.42	4,000
Asphalt concrete (AC)	Binder course	0.38	3,500
Asphalt concrete (AC)	Base course	0.28	3,000
Asphalt rubber (AR)	Wearing course	0.46	6,500
High modulus (HM)	Wearing course	0.48	10,000
High modulus (HM)	Binder course	0.46	8,000
High modulus (HM)	Base course	0.32	6,500
Cement Bound Mixture (CBM)	Foundation course	0.27	2,500
Existing Pavement (EP)	-	0.20	1,500
Existing Pavement (EP)	-	0.22	2,500
Existing Pavement (EP)	-	0.25	3,500

3.3. Catalogue definition

The solutions proposed in the two sheets of the catalogue were designed using the AASHTO method. For this purpose, the following parameters were assumed: reliability R (95 %), layer coefficients a_i (as indicated in Tab. 3), drainage coefficients m_i (1), initial (4.5) and terminal (2.5) values of the Present Serviceability Index (PSI), overall standard deviation S_0 (0.5). For each structure, identified by a certain traffic level (Tab. 2) and a bearing capacity value of the existing foundation/pavement, the number of ETWA80 supported up to the end of life (15 years) were calculated. It was verified that the number of ETWA80 supported by each solution ($ETWA80_S$) was higher than that calculated from the traffic data (i.e., the chosen traffic level, $ETWA80_D$).

Given the structure of the different pavement solutions, a check was carried out using a rational method with the calculation of the main stresses and strains. A three-axes reference system (X, Y, Z) centered with respect to the twin wheel system was used: X and Y identified the horizontal plan (the pavement surface) and Z was the thickness of the road pavement. The hypotheses at the base of the method were: equivalent twin wheels axles of 80 kN (ETWA80), inflation pressure 0.55 MPa, weight on one tire (equal to 2 tons), load footprint radius, points where the stress/strain calculation takes place (in the wheel axle identified by $x = 0$, $y = 0$, and in the twin wheels axle identified by $x = d / 2$, $y = 0$), thicknesses of the pavement layers, material properties (i.e., stiffness, Tab. 3), Poisson coefficients (0.35 for bituminous mixtures, 0.25 for cement bound foundation, 0.40 for subgrade), interface between the layers (bonded or unbounded).

The resistance of the proposed pavement structure against fatigue and rutting was then verified (Kawa et al., 1998). In the "new construction" sheet the following items were evaluated: maximum surface deflection, fatigue of bituminous mixtures and cement bound mixtures, maximum vertical stress and strain of subgrade. In the "maintenance" sheet the maximum surface deflection and fatigue of bituminous mixtures were assessed. Verifying the solutions contained in the "maintenance" sheet, a part of the existing flexible pavement not deteriorated and not removed was considered able to contribute to the overall structure resistance (Tab. 3).

Once selected the work type (new construction or maintenance) and defined the support properties (M_r or CBR for subgrade, or stiffness modulus E of the existing pavement), the column corresponding to the chosen service level was entered to determine the pavement structure. If two alternative solutions were available, they could be considered equivalent in terms of resistance, to be chosen based on needs dictated by specific conditions of the intervention (the latter generally consisted of high-performance materials and were configured with reduced thicknesses). Fig. 2 shows the proposed catalogue sheets.

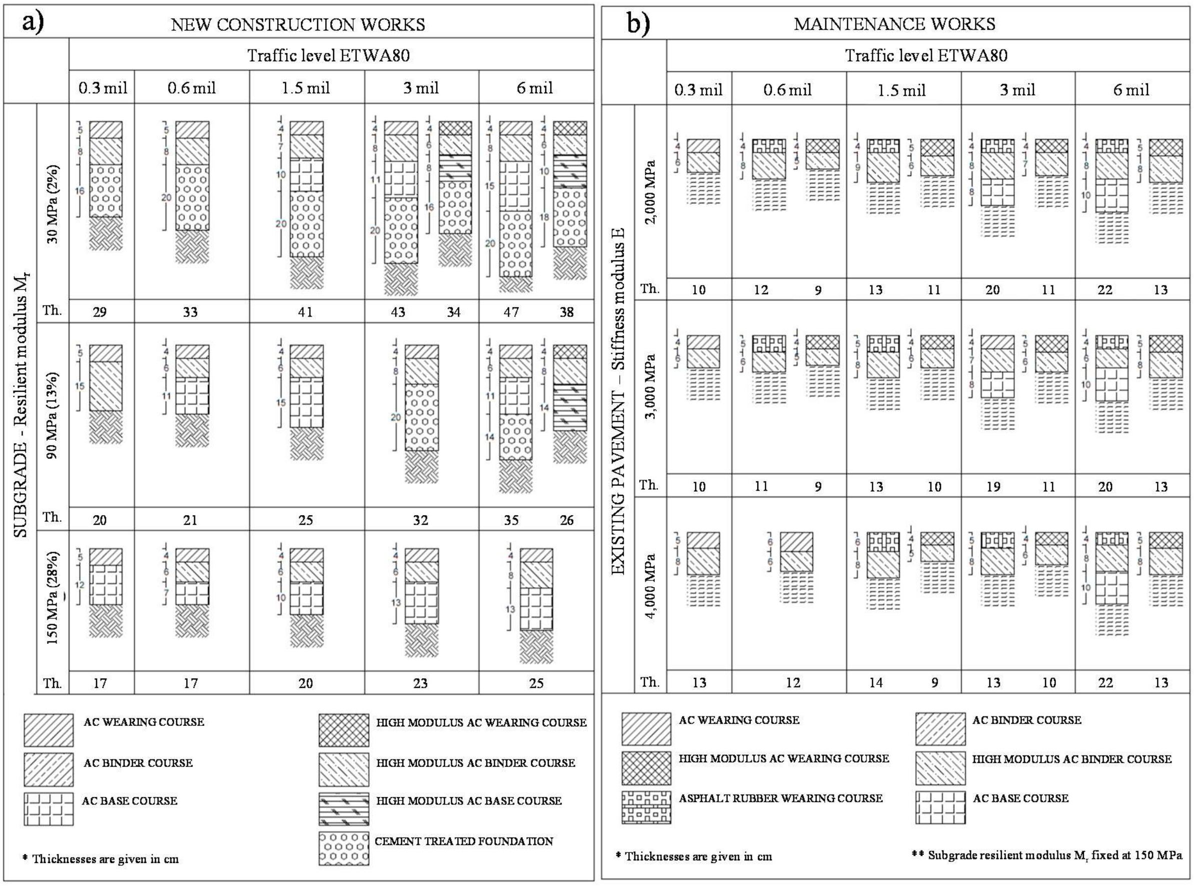

Fig. 2. (a) “New construction” solution of the Catalogue; (b) “Maintenance” solution of the Catalogue.

4. Catalogue case studies application

The solutions proposed in Section 3 were applied to two case studies: a city in northern Italy (Padua) and a city in central Italy (Ancona).

The “Beato Pellegrino” street in Padua between “Mazzini” square and “Fra Paolo Sarpi” street was considered as first case study. Such road is composed by a one-way lane for all vehicles and a one-way bus lane in the opposite direction, allowing a two-way traffic for the public transport service from the suburbs to the center (towards “Mazzini” square). The length of the lane is 700 m and the width varies in function of adjacent buildings facing the street. The lane is separated from the opposite lane by only horizontal marking. The lane is used by two bus lines. Starting from the timetables of the service manager, the number of equivalent axles over 15 years was deduced equal to 1,352,743 ETWA80. The study was envisaged because the current road pavement shows multiple forms of distress, especially along the wheel path. For a maintenance intervention, entering the sheet in Fig. 2. (b) with a service level of 1,500,000 ETWA80 and supposing an average stiffness modulus of 3,000 MPa (existing bituminous mixture not deteriorated and not removed), the traditional solution consists of 0.13 m-thick asphalt layers. For a complete re-construction intervention, entering the sheet in Fig. 2 (a) with a service level of 1,500,000 ETWA80 and assuming a subgrade bearing capacity equal to 90 MPa, the proposed solution has a thickness of 0.25 m.

The city of Ancona was selected as second case study. The bus lane of “Torresi” street was analyzed, between “Ugo Bassi” square and the intersection between “Torresi” and “della Montagnola” streets. The road has a one-way bus lane with direction from the city center (the square) to Tavernelle (the suburbs) and, in the opposite direction, a one-way lane for all vehicles. The length of the lane is approximately 170 m, while the width is equal to 3.50 m with separation by horizontal markings. The lane is used by three bus lines. Starting from the timetables of the service manager, the number of equivalent axles over 15 years was found equal to 2,869,915 ETWA80. Also in this case study, the work was envisaged because the current road pavement presents multiple forms of distress, similarly to Padova case study. For a maintenance intervention, entering the sheet in Fig. 2. (b) with a service level of 3,000,000 ETWA80 and supposing an average stiffness modulus of 3,000 MPa, the traditional solution consists of 0.19 m-thick new asphalt layers. For a reconstruction intervention, entering the sheet in Fig. 2 (a) with a service level of 3,000,000 ETWA80 and assuming a subgrade bearing capacity of 90 MPa, the solution has a thickness of 0.32 m.

5. Conclusions

The Authors proposed in this work a catalogue of road pavements for bus lanes to provide a tool to facilitate technicians (organizations, designers and builders) in identifying the most suitable pavement thickness in relation to the traffic expected during the pavement lifetime. The two catalogue sheets contained various solutions for re-construction or maintenance activities. Each sheet enclosed three conditions of the laying surface (subgrade or existing pavement) and five traffic levels: forty-four design solutions were proposed. The Authors analyzed and determined various parameters to define these solutions: the traffic (buses characteristics and ETWA80 calculation), the subgrade bearing capacity, the materials characteristics and the climatic conditions. They also defined an equation to consider the variability of the line timetables over a year (weekdays, pre-holidays and holidays)

Traditional solutions and high-performance ones were included in the catalogue, the latter allowing lower thicknesses often necessary for works in urban areas. However, the solution choice cannot be separated from a careful assessment of the needs that distinguish each situation. All the proposed structures were designed and verified with criteria and calculation methods available in the literature, starting from the stress-strain state calculation.

Future developments may include the use of geomembranes or geogrids to further improve performance and contain thicknesses during the pavement restoring. Furthermore, specific situations will be considered (intersections and parking areas and bus stops) in which the pavement should be subjected to different stresses if compared to a traffic lane. Historical cobblestone surface layer will be also considered as an option to be included in the proposed catalogue.

This activity will continue to promote the bridging of the knowledge and practice gaps, optimizing the design methods also in view of the actual and future challenges related to traffic magnitude, vehicle complexities and general construction concerns.

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