Pavement life cycle cost analysis for city logistics

F. G. Praticò, L. Amodeo, D. Lamari, C. Lanciano, V. Placido,
M. Praticò & T. Scattareggia
*DIIES – Dipartimento di Ingegneria dell'Informazione,
delle Infrastrutture e dell'Energia Sostenibile,
Università Mediterranea di Reggio Calabria, Italy*

Abstract

As is well known, city terminals in densely populated areas affect traffic, infrastructures, health and the environment.

In more detail, a new terminal has the potential for influencing urban transport strategies, environmental aspects, infrastructure development, city logistics, freight transport, port and city interaction, and life cycle management.

In light of the above facts, the objectives of this study were confined into the preliminary analysis of the life cycle cost (LCCA) associated to several hypotheses in terms of geometric design and pavement design of a new city terminal.

Hypotheses included: a) the choice of the location of the freight terminal (close to railway track, motorway and port of a town having a population of about two hundred thousand people); b) layout and main heavy vehicle paths from/to the terminal; c) equipment; d) main operations; e) dynamic and static loads of equipment; f) pavement design alternatives, construction and quality assurance. Under the above hypotheses, a life cycle cost analysis has been carried out, including rehabilitation alternatives, resurfacing alternatives, analysis period, salvage value, interest and inflation assumptions, present value derivation.

Based on the results obtained, rehabilitation options emerged as a key factor in the minimization of the overall life cycle cost in terms of present values.

Results can benefit both researchers and practitioners.

Keywords: life cycle cost analysis, urban transport, pavement, port, freight terminal, city logistics, urban distribution centre.

WIT Transactions on The Built Environment, Vol 146, © 2015 WIT Press
www.witpress.com, ISSN 1743-3509 (on-line)
doi:10.2495/UT150271

1 Objectives

The objectives of this study were confined into the preliminary analysis of the life cycle cost associated to several hypotheses in terms of geometric design and pavement design of a new freight terminal, which is supposed to be located in Southern Europe (Italy, Reggio Calabria town).

The paper is organized as follows: the Introduction illustrates container/ freight terminals main areas, operations, and solutions in terms of pavement. The section layout and tentative geometric design focuses on the layout of the terminal area.

Section tentative pavement design and LCCA deals with the preliminary design of pavement and life cycle cost analysis.

Finally, conclusions are drawn.

2 Introduction

City terminals are carrier-operated facilities whose primary functions are the intramodal (e.g., truck to truck) sorting and consolidation of load sets between intercity linehaul (truck routes) and local pickup and delivery, as well as the management of pickup and delivery services to customers [1, 2].

According to the Institute of City Logistics, this latter refers to the process for totally optimizing the logistics (i.e., the management of the flow of goods) and transport activities by private companies in urban areas while considering the traffic conditions, congestion issues and combustible consumption, with a view to reduce the number of vehicle on the cities, through the rationalization of its operations.

Freight/city terminals in densely populated areas affect traffic, infrastructures, health and environment. In more detail, a new terminal has the potential for influencing urban transport strategies, environmental aspects, infrastructure development, freight transport, port and city interaction, and life cycle management.

The importance of the intermodal freight connectors from the perspective of the agencies derives from the fact that they are key conduits for the timely and reliable delivery of goods and hence it is important to evaluate the condition and performance of connectors and related investment [3].

Last-mile and long distance logistics [4, 5], microsimulation in the city terminal [6], and urban regeneration aspects [7] are other relevant topics not discussed in the following.

Typical container terminal areas include equipment parking, automobile parking, intermodal yard, gate facilities and secondary gate facilities, wheeled container storage, grounded container storage, expansion areas, wharf areas (pier areas).

Operations include [8]:

- on-Dock Operations (container vessel arrives at the marine terminal; specialized cranes unload containers from the ship; straddle carriers pick up containers from wharf);

- container yard operations (containers are stored in the yard until they are picked up by a heavy duty vehicle or loaded onto a train; straddle carriers remove the container from storage areas and load it onto trucks);
- gate operations (loaded trucks and trains are processed at the gate and depart for their final destinations);
- container operations (rubber-tire gantry cranes (RTGs) are used to load containers onto trucks and to make up trains)

Equipment characteristics are summarised in table 1.

Table 1: Equipment characteristics.

	Load per wheel		Contact pressure	
Equipment Type	Kips	KN	Psi	MPa
Yard Hustler	4.5	20.0		
Reach Stacker	40.1	178.3		
Side Pick	0.5	2.1		
Top Pick	60.3	268.2		
Straddle Carrier	33.8	150.3		
Rubber-Tire Gantry	52.0	231.3		
4-High Cont.St.			1000.0	6.9
5-High Cont.St.			1126	7.8
Dolly Wheels /Shoes			5000.0	34.5

Main equipment pieces include [9]:

- terminal tractor;
- double stack train (containers are stacked two high on railroad cars);
- rubber tire gantry (RTG), straddle carrier, top loader or other similar equipment, and rail mounted gantry (RMG), front end loader (FEL);
- container handling equipment: FELs, RTGs, strads, hustlers with bomb carts (shuttle chassis), hustlers with chassis, and street legal trucks with chassis.

For pavement design, the pavement is subject to both dynamic loading (container handling Equipment, pressures about 1 MPa) and static loading (from corner castings on containers and either dolly wheels or sand shoes on the chassis, see Table 1, and [8], pressures about 2–35 MPa). The main steps for the design include site investigation, design, construction, and quality assurance management. Hot mix asphalt (HMA) pavements are not usually used in areas subject to heavy wheel loads (permanent deformation). While PCCP (Portland Cement Concrete Pavements, jointed or continuously reinforced) are considered appropriate for most operational areas, RCCP (Roller Compacted Concrete Pavement) is best suited for large areas subject to heavy loading conditions (see references in Table 2). Under appropriate design, innovative pavements can be adopted in freight connectors [10].

Table 2: Example of pavements.

Code	Type of Pavement	Ref.
(1)	N1: 3''AC+16.5''RCC+6''ABC+4''#78 Stone+geotextile material+8'' CBR20 (Roller Compacted Concrete (RCC) with 3-inch AC Wearing Surface)	[8]; [11]
(1)	N2:4'' Paver+1'' Bedding course + 16.5''CTB + 6''ABC + 12'' CBR20 (Interlocking Concrete Paver Blocks (ICPB) on Cement Treated Base (CTB))	[8]; [12]
(1)	N3:12''PCC+6''ABC+#78 Stone + Geotextile material + 8''CBR20 (Portland Cement Concrete -PCC)	[8]
(1)	N4: 14''AC+6''ABC+8''CBR20 (Asphaltic Concrete – AC, on Crushed Aggregate Base CAB)	[8]
E1	E1: 12 cm concrete bricks+5 cm gravel+33 cm sand cementation+1÷1.5 m compact sand	[13]
P1-P3	P1-P3: Hydraulic-cement concrete pavement with 35 cm thick in the container yard and 40 cm thick in the quayside (or 30cm). (30–40cm PCC+30cm aggregate base-estimated)	[14]
P2	P2: Hydraulic-cement concrete pavement with 30 cm thick in the container yard. See above	[14]
H1	H1: 80 mm (3.125 in.) thick interlocking concrete block pavers+25 mm (1 in.) bedding sand+ 200 mm (8 in.) AC base+ and 450 mm (18 in.) aggregate base + the 150 mm (6 in.) subgrade/geotextile reinforcement	[15]
(2a)	D1: 4cm densiphalt +8-9cm bituminous binder course+8-18cmbituminous base course+25-30cm Crushed stone base +20-40cm subbase2. Notes. High modulus asphalt binder course. Crushed stone base. Alternative use of granular base influences the course thickness. The thickness of Subbase 2 depends on the need for frost protection.	[16]
(2b)	D2: 4cm densiphalt +6.5-8cm bituminous binder course+6.5-10cm bituminous base course+20-25cm crushed stone base +20-35cm subbase2. Notes. High modulus asphalt binder course. Crushed stone base. Alternative use of granular base influences the course thickness. The thickness of Subbase 2 depends on the need for frost protection.	[16]; [17]; [18]; [19]

Symbols and notes.
(1): Norfolk International Terminals South; (2a): semi-flexible pavements heavy loaded Areas (The design resists 2000 annual operations from heavy equipment e.g. DRD450-65S5 Reach Stacker.); (2b): semi-flexible pavements medium loaded Areas (The design resists 500 annual operations from heavy equipment e.g. DRD450-65S5 Reach Stacker.); E1: Europe Container Terminus, Rotterdam; P1-P3: Port of Valparaíso; H1: Howland Hook Marine Terminal [15]; AC: Asphalt concrete; RCC: Roller Compacted Concrete; ABC: Asphalt pavement, brick and concrete (ABC) rubble; #78: Processed coarse limestone aggregate with a grade of 1/2" to No. 4 (4.75mm); geotextile material: Geotextiles are permeable fabrics which, when used in association with soil, have the ability to separate, filter, reinforce, protect, or drain. Typically made from polypropylene or polyester; CBR20: subgrade with a CBR of 20.

3 Layout and tentative geometric design

Figures 1 to 3 show the terminal organization and vehicles paths from and to the area. Figure 1 points out the terminal location at the centre of the Mediterranean sea (city of Reggio Calabria-Italy). The use of urban road transportation assignment models in emergency conditions and the study of spatial economic transport interaction processes at urban scale will be carried out in order to optimize the preliminary layout [20, 21]. In Figure 2 road paths from and to the A3 motorway are pointed out (site layout includes terminal facility as well as railway track and port). The A3 motorway runs across South Italy from Salerno to Reggio Calabria. Importantly, this terminal would be located along the Scandinavian-Mediterranean Corridor, which is a north–south corridor which aims at integrating several European priority projects, European Rail Traffic Management System (ERTMS) corridor B, and RailFreight Corridor 3. This is a crucial axis for the European economy, linking the major urban centres in Germany and Italy to Scandinavia and the Mediterranean. Note that the above city terminal would positively interact also with Reggio Calabria port, Villa san Giovanni port, and with Gioia Tauro harbour. This latter is classified as a commercial and industrial port, and is primarily a transshipment hub. In Figure 3 (both on left and right), terminal building (TB), paths for light duty (LD), medium duty (MD) and heavy duty (HD) trucks are tentatively pointed out.

Figure 1: Gioia Tauro, Villa San Giovanni and Reggio Calabria harbours and Reggio Calabria city terminal.

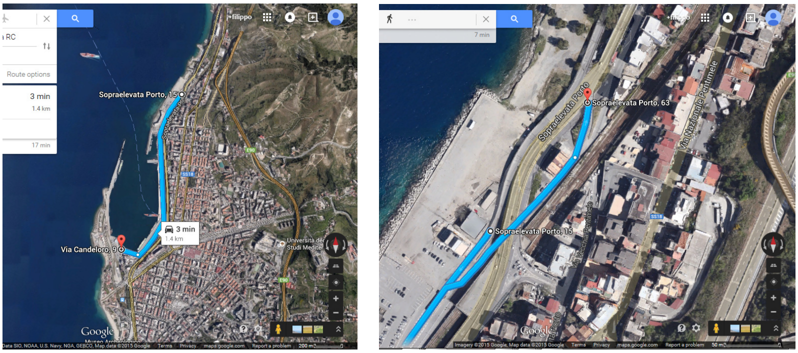


Figure 2: Road path from (left)/to (right) A3 motorway end point to/from the area of the city terminal.

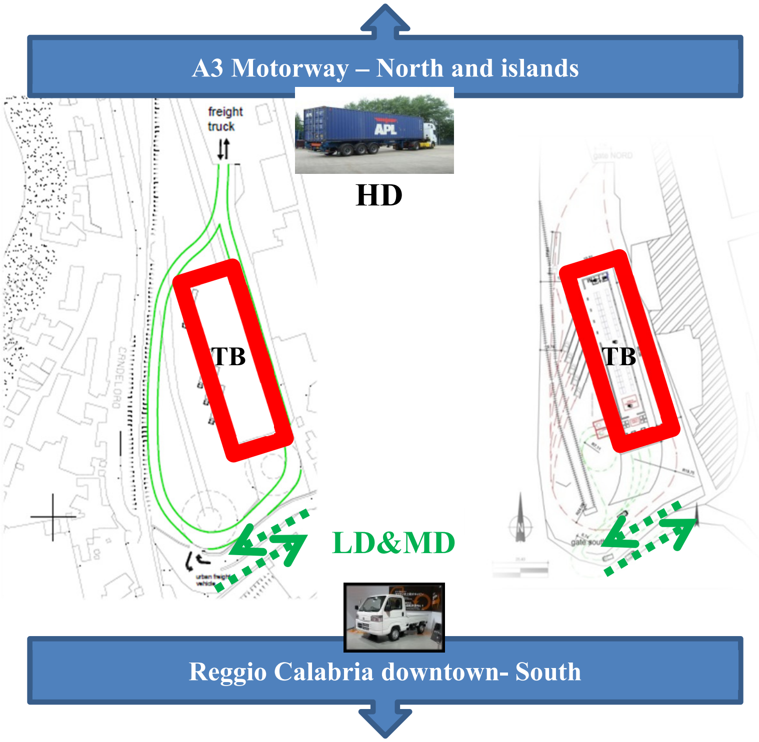


Figure 3: Tentative geometric design.

4 Tentative pavement design and LCCA

Tables 3–5 and Figures 4–6 summarize pavements considered (see also [8] and Table 2), and the preliminary life cost analysis (LCCA) carried out. In more detail, note that: i) Table 3 lists the construction costs of the solutions which authors preliminarily considered. Costs ranged from 45 up to 155 €/m2; ii) Tables 4–6 include the main mechanistic inputs used to derive strains and stresses (pavement types L1–L12, see also [9, 21, 23, 24]); iii) Figures 4–6 illustrate the main outputs of the LCCA.

Pavement design was carried out through Kenlayer software [9, 25]. This permitted to derive: a) horizontal strains/principal tensile strains at the bottom of the asphalt concrete layer; b) and the vertical/principal compressive strain at the top of the subgrade. Consequently, by using appropriate fatigue laws, it was possible to calculate: 1) repetitions until asphalt concrete starts cracking; 2) repetitions until subgrade starts rutting. Afterwards LCCA analyses were carried out. LCCA is an engineering-economic analysis tool which compares the relative merits of competing project implementation alternatives. Minimizing the pavement life cycle costs (present worth value, PWV or PV, or equivalent uniform annual cost, EUAC) will increase the sustainability of the pavement

Table 3: Construction costs (approximate estimates, see table above).

Type of pavement	**Cost (€/m2)**
N1: 3''AC+16.5''RCC+6''ABC+4''#78 Stone+geotextile material+8''CBR20	104.31
N2: 4'' Paver+1'' Bedding course+16.5''CTB+6''ABC+12'' CBR20	84.75
N3: 12''PCC+6''ABC+#78 Stone+Geotextile material+8''CBR20	71.25
N4: 14''AC+6''ABC+8''CBR20	110.45
E1: 12 cm CB+5 cm gravel+33 cm sand cementation+1÷1,5 m compact sand	109.04
P1: Hydraulic-cement concrete with 35 cm thick in the container yard + 30 ABC	63.10
P2: Hydraulic-cement concrete pavement with 40 cm thick in the quayside + 30 ABC	70.62
P3: Hydraulic-cement concrete pavement with 30 cm thick in the quayside + 30 ABC	55.58
H1: 80 mm blocks+ 25 mm sand+ 200 mm AC+ 450 mm base+ 150 mm subgrade r.	154.61
D1: 4cm D +8-9cm binder course+8-18cm base course+25-30cm B+20-40cm SB	87.83
D2: 4cm D +6.5-8cm binder course+6.5-10cm base course+20-25cm B+20-35cm SB.	78.64
L1: 3 + 4 AC on 15 CMB	45.17
L2: 3 + 4 AC on 17 CMB	46.94
L3: 3 + 4 AC on 19 CMB	48.72
L4: 3.5 + 4.5 AC on 14 CMB	48.92
L5: 3.5 + 4.5 AC on 16 CMB	50.70
L6: 3.5 + 4.5 AC on 18 CMB	52.47
L7: 3 + 4 + 2 AC on 13 CMB	50.23
L8: 3 + 4 + 2 AC on 15 CMB	52.00
L9: 3 + 4 + 2 AC on 17 CMB	53.78
L10: 3.5 + 4.5 + 2 AC on 12 CMB	53.99
L11: 3.5 + 4.5 + 2 AC on 14 CMB	55.76
L12: 3.5 + 4.5 + 2 AC on 16 CMB	57.54
Symbols. AC: asphalt concrete. CMB: crushed miscellaneous base; B: base; SB: subbase; see table above; CB: concrete bricks.	

Table 4: Material characteristics for pavement type L1 (L1: 3 + 4 AC on 15 CMB).

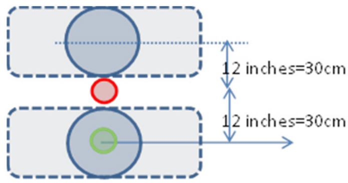
Thickness coefficient	Material	Elastic modulus	Poisson
3 inches=7.5cm	Asphalt concrete	450,000psi=31,500daN/cm^2	0.35
4 inches=10 cm	Asphalt concrete	550,000psi=38,500daN/cm^2	0.35
15 inches=37cm	Crushed miscellaneous base	63000psi=4410 daN/cm^2	0.35
Infinite	Subgrade	18500psi=1295 daN/cmq	0.4

Table 5: Material characteristics for pavement type L10 (3.5 + 4.5 + 2 AC on 12 CMB).

Thickness	Material	Elastic modulus	Poisson coefficient
3.5 inches	Asphalt concrete	450,000psi=31,500daN/cm^2	0.35
4.5 inches	Asphalt concrete	550,000psi=38,500daN/cm^2	0.35
2.0 inches	Asphalt concrete	300000psi	0.35
12 inches	Crushed miscellaneous base	63000psi=4410 daN/cm^2	0.35
Infinite	Subgrade	18500psi=1295 daN/cmq	0.4

Table 6: Main load parameters.

Radius	11.02	In
Diameter	56	cm
Surface Area	2461	cm^2
Pressure	120	Psi
Pressure	8	daN/cm^2
Load (1 Tyre)	20380	daN
Load (2 Tyres)	40761	daN
Load (4 Tyres=1 Axle)	81521	daN
Dual Wheel Load	91513	Lbs



system (see [26–30]). The detailed analysis of the costs over the entire life cycle of the transportation infrastructure (LCCA, with respect to the zero option – traditional transportation facilities) can assess the decrease of agency (AC, e.g., maintenance and rehabilitation), user (UC, e.g., time, accidents, vehicle operating costs, see [31, 32]), and externality (EC, e.g., related to CO_2e emissions, etc., [33, 34]) costs.

Figure 4: Expenditure stream diagram for a pavement design alternative (solution L9: 3 + 4 + 2 AC on 17 CMB; C=53.78 €/m^2).

Figure 5: Expenditure stream diagram for a pavement design alternative (solution L12: 3.5 + 4.5 + 2 AC on 16 CMB; C=57.54€/m^2).

Main costs include construction costs (CC), rehabilitation costs (RC), resurfacing costs (RES) and salvage values (SV, negative values in Figures 4 and 5).

Data gathering and analysis are still in progress. This notwithstanding the following preliminary observations can be proposed: i) solutions L1, L2, L4, and L5 yielded the worst results, due to the unsatisfactory expected life, which implied the increase of the present value (PV) of costs over life and then a very high extra cost in percentage (EC, %, y-axis); ii) solutions L3, L5, L6, L7, L10 yielded an appreciable increase of the PV and an extra cost in percentage between 20 and 40%. The reason of this slight improvement in terms of LCCA was usually either a good balance between rutting-related and cracking-related life or a very high rutting-related life; iii) finally, solutions L8, L9, L11, and L12 yielded the best result because of the very high rutting-related life.

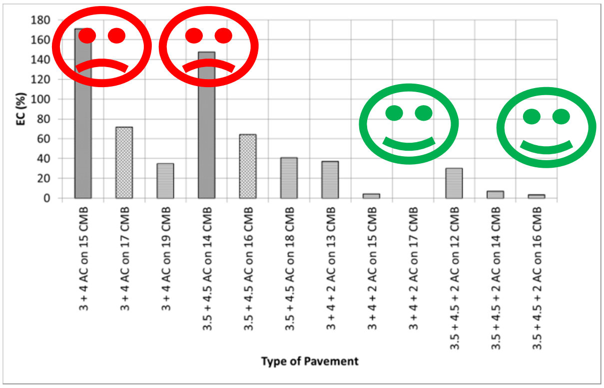


Figure 6: EC (%) for different pavement design alternatives (solutions L1–L12).

5 Conclusions

City terminals have the potential for influencing urban transport strategies, environmental aspects, infrastructure development, city logistics, freight transport, port and city interaction, and life cycle management.

In the light of the above facts, the objectives of this study were confined into the preliminary analysis of the life cycle cost associated to several hypotheses in terms of geometric design and pavement design of a new city terminal.

Under the above hypotheses, a life cycle cost analysis has been carried out, including rehabilitation alternatives, resurfacing alternatives, analysis period, salvage value, interest and inflation assumptions, present value derivation. Based on the results obtained the following conclusions may be drawn: a) rehabilitation options are a key factor in the minimization of the overall life cycle cost in terms of present values; ii) the balance between the expected life of the aggregate base course and the expected life of the asphalt concrete layers plays an outstanding role in the rehabilitation and resurfacing processes and greatly affects present values and extra costs. Further research is still needed in the aim of pursuing a more comprehensive understanding of long-terms effects of rehabilitation options.

Results can benefit both researchers and practitioners.

Acknowledgements

L. Amodeo, D. Lamari, C. Lanciano, V. Placido, M. Praticò, T. Scattareggia collaborated with the application as students of the Master in Transportation Engineering, supplied in 2014–2015 at the Dipartimento di Ingegneria dell'Informazione, delle Infrastrutture e dell'Energia Sostenibile of Università Mediterranea di Reggio Calabria.

References

[1] NCFRP Report 13: Freight Facility Location Selection: A Guide for Public Officials, Transportation Research Board, Washington, D.C. 2011, 2011.

[2] Praticò F.G., Puppala A.J., Lime and Cement Treatments of Subgrades in Southern Italy: Facing Interports Issues And Challenges, SIIV – 5th International Congress – Sustainability of Road Infrastructures, Procedia – Social and Behavioral Sciences, *2012*. E201994 – issn: 1877-0428.

[3] Rice, D, (2011). Intermodal Freight Connectors: Pavement Condition, Update, January 2011, CMAP Congestion Management Process. http://www.cmap.illinois.gov/documents/10180/27573/Intermodal-Connectors-Pavement-Condition-Update_January-31-2010_final.pdf/a5f0cff6-87af-4608-a3ae-9869098d2d18, 2009.

[4] Amodeo L., Lamari D., Musolino G., Placido V., Polimeni A., Praticò M. & A. Vitetta, An ex-ante evaluation of last-mile freight distribution services for city logistics In WIT Transactions on the Built Environment, volume 146, 2015. ISSN: 1746-4498, Digital ISSN: 1743-3509.

[5] Russo F., Rindone C., D'Agostino P., Lanciano C. & Scattarreggia T., Long distance freight transport to the provisioning of a city logistics. In WIT Transactions on the Built Environment, volume 146, 2015. ISSN: 1746-4498, Digital ISSN: 1743-3509.

[6] Gattuso D., Cassone G.C., Lanciano C., Placido V. & M. Praticò. A freight urban distribution center design with micro-simulation support for city logistics. In WIT Transactions on the Built Environment, volume 146, 2015. ISSN: 1746-4498, Digital ISSN: 1743-3509.

[7] Panuccio P, Amodeo L., D'Agostino P., Lamari D. & T. Scattarreggia. Urban regeneration and smart city according EU strategies: urban distribution center in city logistics. In WIT Transactions on the Built Environment, volume 146, 2015. ISSN: 1746-4498, Digital ISSN: 1743-3509.

[8] Crist, M.T. Pavement Design for Containerized Cargo Terminals. Retrieved in February, 2015 from: http://www.secement.org/PDFs/8%20CRIST%20-%20RCC%20at%20NIT.pdf, 2005.

[9] Moffatt & Nichol, Container terminal and intermodal rail yard operational area consideration for pavement design, 2006 http://www.portoflosangeles.org/pdf/Port_Pavement_Design_Guide.pdf.

[10] Praticò F.G., Moro, A., D'Agostino, P., An experimental investigation on innovative pavements for city logistics. In WIT Transactions on the Built Environment, volume 146, 2015. ISSN: 1746-4498, Digital ISSN: 1743-3509.

[11] Boyd, B., Roller Compacted Concrete CN Intermodal Project, 2002. Retrieved in March, 2015 from http://www.standardgeneraledmonton.ca/site/sge/content/file/CNIntermodal.pdf.

[12] Ishai, I., Yaacobi, S., and Brown-Cohen, S., Design And Construction Of Concrete Block Pavements For Heavy Duty Railway Freight Terminal, 8th International Conference on Concrete Block Paving, San Francisco, California USA, http://www.sept.org/techpapers/1360.pdf, November 6–8, 2006.

[13] Van Leeuwen, H., Use of block paving in European ports, Proc. 1st Int. Conf. on CBP, Pages: 65-69. Retrieved from: http://www.icpi.org/sites/default/files/techpapers/78.pdf, 9-1980.

[14] Port of Valparaíso. Retrieved in February, 2015 from: http://www.sanantonioport.cc.cl/html/licitaciones/SEC6.pdf

[15] Sieglen, Jr., W. and von Langsdorff, H. Interlocking Concrete Block Pavements at Howland Hook Marine Terminal. Ports: pp. 1-10. doi: 10.1061/40727(2004)131. Retrieved from: http://www.uni-groupusa.org/PDF/HowlandHookPaper.pdf, 2004.

[16] Densiphalt. Retrieved from: http://www.densit.com/Business_Areas/Industrial_Flooring_and_Pavements/Densiphalt®/Ports.aspx, in February, 2015.

[17] Levine, K.K. (2001). Cool Pavements Research and Technology. Retrieved from: http://www.dot.ca.gov/newtech/researchreports/preliminary_investigations/docs/cool_pavements_preliminary_investigation.pdf, February 2015.

[18] OECD – Organisation for Economic Co-Operation and Development. Economic Evaluation of Long-Life Pavements, 2005. Retrieved in February 2015 from: http://www.internationaltransportforum.org/pub/pdf/05PavementI.pdf

[19] Jacobsen S. The Effectiveness Of Grouted Macadam At Intersections – A Life-Cycle Cost Perspective, 2012 Retrieved from: http://www.diva-portal.org/smash/get/diva2:549667/FULLTEXT01.pdf, February 2015.

[20] Di Gangi M., Musolino G., Russo F., Velona P., Vitetta A. Analysis and comparison of several urban road transportation assignment models in emergency conditions. In: C.A. Brebbia, D. Fayzieva (eds). Environmental Health Risk II, WIT Press, pp. 247-257, 2003.

[21] Russo F. & Musolino G. A unifying modelling framework to simulate the Spatial Economic Transport Interaction process at urban and national scales. Journal of Transport Geography, 24, pp. 189-197, 2012.
[22] Praticò, F. G., and Moro, A. (2011). "In-lab and on-site measurements of hot mix asphalt density: Convergence and divergence hypotheses." Constr. Build. Mater., 25(2), 1065–1071. doi:10.1016/j.conbuildmat.2010.06.071.
[23] Praticò F.G., Moro A., Ammendola R., Factors Affecting Variance and Bias of Non-Nuclear Density Gauges For PEM AND DGFC, The Baltic Journal of Road and Bridge Engineering, 1822-427X, 1822-4288 on line, – 2009, 4(3): 99–107.
[24] Khazanovich, L., Celauro, C., Chadbourn, B., Zollars, J., Dai, S., Evaluation of subgrade resilient modulus predictive model for use in mechanistic-empirical pavement design guide, Transportation Research Record, (1947), pp. 155-166, 2006.
[25] Huang, Y.H., Pavement Analysis and Design (2nd Edition), August 18, 2003.
[26] Douglas, D. G., and R. K. Molenaar. Life-Cycle Cost Award Algorithms for Design/Build Highway Pavement Projects, Journal of Infrastructure Systems, 2004, Vol. 10, No. 4.
[27] Walls, J., Smith, M.R., Life-Cycle Cost Analysis in Pavement Design-Interim Technical Bulletin, FHWA-SA-98-079, 1998. Retrieved from: http://www.wsdot.wa.gov/NR/rdonlyres/7A7CC34A-6336-4223-9F4A-22336DD26BC8/0/LCCA_TB.pdf, March 2015.
[28] Wilde, W. J., S. Waalkes, and R. Harrison. Life Cycle Cost Analysis of Portland Cement Concrete Pavements, Report No. FHWA/TX-00/0-1739-1, U.S. Department of Transportation, 1999.
[29] FHWA (2002). Life-Cycle Cost Analysis Primer 2002, Office of the Asset Management, United States Department of Transportation, August 2002, p. 25.
[30] Praticò F.G., Casciano A. Variability of HMA characteristics and its influence on pay adjustment, Journal of Civil Engineering and Management 21 (1), 119-130, 2015.
[31] Mucka, P. Relationship between International Roughness Index and straightedge index. Journal of Transportation Engineering ASCE, 138 (9), 1099–1112, 2012.
[32] Praticò F.G., Vaiana R., A study on volumetric versus surface properties of wearing courses, Construction and Building Materials, 38, pp. 766-775, Jan 2013, doi:10.1016/j.conbuildmat.2012.09.021.
[33] Praticò F.G. & Vaiana R., Improving infrastructure sustainability in suburban and urban areas: is Porous asphalt the right answer? And how?, Urban Transport: Urban Transport and the Environment in the 21st Century, Edited by: C. A. Brebbia, J. W. S. Longhurst, WIT Press, ISBN: 9781845645809, WIT Transactions on Ecology and the Environment, 2012, pp. 673-684.
[34] Praticò, F.G., On the dependence of acoustic performance on pavement characteristics, Transportation Research Part D 29 (2014) pp.79-87.