Transportation Research Part A 92 (2016) 162–183

Contents lists available at ScienceDirect

Transportation Research Part A

journal homepage: www.elsevier.com/locate/tra

Capacity and safety analysis of hard-shoulder running (HSR). A motorway case study

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ARTICLE INFO

Article history:
Received 11 July 2016
Accepted 2 August 2016

Keywords:
Hard-shoulder running
Capacity
Safety
HSM
Reliability
Variable speed limit

ABSTRACT

Operational motorway conditions can be improved by introducing traffic flow management and control systems, such as ramp metering (RM), high occupancy vehicle (HOV) lanes, real-time variable speed limits (VSLs), reversible lanes (RL), automated highway systems (AHS) and hard-shoulder running (HSR). The effects of such devices need to be examined in terms of capacity and safety. This paper examines the case study of the Italian motorway A22, which is supposed to be equipped with an HSR system implemented along 128 km in order to reduce congestion with consequent improvement in levels of service (LOS). We studied the traffic processes (capacity, flow distribution between lanes, reliability, etc.) and estimated the expected capacity and safety conditions. These latter were studied with the method provided by the Highway Safety Manual (HSM), as well as by undertaking sensitivity analyses to quantify the expected changes in crash frequency at varying HSR activation hours (from 30 to 200 h) in a year. It has been observed that HSR activation does not involve significant variations in the general safety conditions in the presence of a considerable capacity increase up to 35%. Moreover, have been identified the cases which require speed limit implementation (with VSLs system) in function of the values of reliability ϕ and velocity process $\overline{V}$, and also suggested a speed limit sign system.

1. Introduction

The increase in highway transport demand causes numerous problems, such as deteriorated levels of service (LOS), congestion (oversaturation), delays, queue formation, higher energy consumption and pollutant emissions, and inadequate safety conditions (Li et al., 2014). In order to alleviate these problems, we can intervene in infrastructures (e.g. additional lanes, geometric design improvement, etc.) or in traffic flow management and control. The latter are particularly advantageous in that they are environmentally sustainable and relatively cheap (Li et al., 2014) since they exploit the existing physical infrastructures. The most well-known highway traffic control systems are truck policies, ramp metering (RM), high occupancy vehicle (HOV) lanes, real-time variable speed limits (VSLs), reversible lanes (RL), automated highway systems (AHS) and hard-shoulder running (HSR).

The ramp metering aims to control and regulate traffic flow in and out of highways in order to obtain the intended operating conditions, for example in terms of LOS (Ramp Management and Control, Handbook, 2006; Papageorgiou et al.,1991).

VSL systems can be implemented to ease traffic congestion (by homogenizing vehicle driving speeds) and to increase safety (Elefteriadou, 2014) with consequent 5–17% reduction in crashes (Lee et al., 2006; Elefteriadou, 2014).

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http://dx.doi.org/10.1016/j.tra.2016.08.003
0965-8564/

In AHS automated or semi-automated vehicles, driving singly or in platoons, in dedicated and properly equipped lanes, expand the lane capacity up to 8000 veh/h (Ioannou et al., 1997). Other advantages are the reduction in fuel consumption and a sheer drop in pollutant emission values (up to 27%). In AHS vehicles drive in platoons (composed of no more than 20 vehicles), with inter-vehicle distances of 1–2 m, with a 30–60 m interval between them (Ioannou et al., 1997). Numerous research projects (e.g. ARAMIS, PROMETHEUS, VITA II, SARTRE, HAVEit, etc.) have shown AHS benefits (Carbaugh et al., 1998; Papacostas and Prevedouro, 2001; Michael et al., 1998; Hamouda et al., 2009).

Hard-shoulder running (HSR) is a scheme enabling hard shoulders to be temporarily open to ordinary traffic, together with general-purpose lanes, during peak demand hours. Some studies have shown that HSR can be also used in urban contexts as a support of smart cities (Wang et al., 2016). Sometimes priced dynamic shoulder lanes (PDSL) can also be of help (NCHRP, 2012).

France, Holland and Germany were the first to introduce HSR in highways (Lemke and Moritz, 2001; Mattheis, 2002; Moritz and Wirtz, 2003). In Germany its use dates back to 1996 (BBC News World Edition, 2004; Lemke and Irzik, 2006); today it is used on a 200 km-long highway network, with a 100 km/h speed limit. In Holland HSR, built since 2003, is nowadays implemented on around 1000 km highway network. In Great Britain it has been working since 2006, with a 50 mph speed limit. In Italy it is implemented on A14 (23.6 km-long) and on "the Mestre bypass motorway". In North America HSR installations are numerous: in San Diego (California) since 2005 on Highway I-805/SR 52 (the system operates when traffic slows to 30 mph or lower), in Delaware, in Florida since 2005 on Highways SR 826 and SR 836, in Georgia on Highway GA 400 since 2005 (the system operates when traffic slows to 35 mph or less), in Maryland on Highway US 29 (with 55 mph as maximum speed limit), and finally in New Jersey, Virginia and Washington. Experiences on Dutch highways have shown a capacity increase of 7–22 per cent (Kuhn, 2010; Elefteriadou, 2014; Taale, 2006). In Germany capacity increases up to 25%, reduction in travel time up to 20% (FHWA, 2010) and in air and sound pollution (Brinckerhoff, 2010) have been measured. In general but especially in Europe (particularly in Germany, Holland, England), HSR has been combined with VSLs (whose speed is signalled by variable message boards) (Elefteriadou, 2014).

When designing HSR we should keep in mind a lot of factors which can affect its safety (e.g. hard shoulder width (Gross et al., 2009; HSM, 2010)); conflicts at access ramps; sight distance; conflicts with motorists pulling onto the shoulder for emergency purposes; need for bus driver training; speed differential between the general purpose lanes and the shoulder; return merge distance adequacy; debris hazards on shoulder; reduced bridge clearance; drainage; emergency refuge areas (Kuhn, 2010)).

This research focuses on the case study of the HSR plan for the A22 motorway ("Brenner motorway"). The operational motorway conditions and forecast capacities and expected crash frequencies (on the basis of the current configuration) have been analysed. To this end has been used the methodology in the Highway Safety Manual (AASHTO, 2010). The study also involved a sensitivity analysis on the annual hours when HSR is assumed to be open to traffic.

2. Case study: implementing a hard-shoulder running (HSR) measure on A22

The Brenner motorway (A22) is part of the trans-European road network TEN-T (specifically the Helsinki–La Valletta corridor (V), see Regulation (EU) N. 1316/2013). Therefore, the A22 is subject to the rules in the "Directive 2008/96/CE of the European Parliament and Council" (obligation to perform the Road Safety Impact Assessment – RSIA for road infrastructure interventions or traffic management), and has then a crucial role among the European and Italian national transport infrastructures.

Currently the Brenner motorway A22 is 313-km long and has 24 toll booths, 4 junctions with other motorways (A1 North, A1 South, A4 East and A4 West) (Fig. 1). The road has two lanes (3.75-m wide each) in each direction and right-hand hard shoulders, each 3.45 m-wide; the central reservation is 1.20 m-wide (see Figs. 1 and 2).

The study forecasts the HSR implementation from Egna (km 102+00) to Verona North (km 230+00) for 128 km in total; the passing lanes are 6 (3 in each carriageway) in this configuration. To this end we assessed the operational conditions of the infrastructure (traffic curves, capacity, critical density, speed levels etc.) and estimated the variation in accident frequency by means of the HSM methodology (HSM, 2010).

3. Theory

3.1. Some traffic flow theories

This paragraph provides the fundamentals of the traffic flow theory underlying the performed analyses, whose results are given in the following sections. For further details and in-depth analyses see May (1990), Elefteriadou (2014), and Mauro (2015). The study on functionality was carried out with macroscopic flow models which describe traffic flows as liquid or gas motion. Dynamic variables are quantities locally aggregated such as traffic density k(x, t), flow q(x, t), average speed v(x, t), or its variance $\sigma^2 v(x, t)$. Since these aggregations are local, these quantities generally vary over space (x) and time (t).

The main equation formally representing this theory is the conservation equation (Gerlough and Huber, 1975; Kühne et al., 1992; Barceló, 2010):

$$\frac{\partial q(x,t)}{\partial x} + \frac{\partial k(x,t)}{\partial t} = 0 \tag{1}$$