Accident Analysis and Prevention 75 (2015) 119–127

Contents lists available at ScienceDirect

Accident Analysis and Prevention

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

Experimental research on the effectiveness and adaptability of speed reduction markings in downhill sections on urban roads: A driving simulation study

Han Ding [a], Xiaohua Zhao [a,*], Jian Rong [a], Jianming Ma [b]

[a] College of Metropolitan Transportation, Beijing University of Technology, Beijing 100124, PR China
[b] Traffic Operations Division Texas Department of Transportation Austin, TX 78701-2483, USA

ARTICLE INFO

Article history:
Received 12 March 2014
Received in revised form 17 November 2014
Accepted 22 November 2014
Available online 27 November 2014

Keywords:
Speed reduction markings
Effectiveness
Adaptability
Driving simulator
Downhill sections
Roadway grade

ABSTRACT

The objective of this paper is to test the effectiveness and adaptability of speed reduction markings (SRMs) in downhill sections on urban roads with distinct roadway grades. Empirical data including vehicle speed and acceleration were collected in a driving simulator. Subjective questionnaires were conducted, and two indexes – the relative speed difference and standard deviation of acceleration – were developed to evaluate the effectiveness and adaptability of SRMs. Meanwhile, the effectiveness of driving simulator related to different road alignments and types of SRMs has been validated through a field test. Results of subjective questionnaires showed that the majority of subjects had no feelings of nervousness, but they were affected by SRMs while driving through downhill sections in all four scenarios (i.e., downhill sections with vertical grades of 3, 2, 1.5 and 1%). In terms of vehicle speed and acceleration, the results of the analysis of variance (ANOVA) and the contrast analysis (S–N–K method) indicated that SRMs were significantly effective when roadway grades of downgrade sections were 1.5, 2 and 3%, while transverse speed reduction markings (TSRMs) had significantly worse adaptability ($P < 0.05$). Therefore, this research recommends that TSRMs could be placed in downhill sections with roadway grades of 1.5 or 2%; longitudinal speed reduction markings (LSRMs) could be placed in downhill sections with a roadway grade of 3%. Whether SRMs are placed in downhill sections with a roadway grade of 1% would depend on other factors such as financial issues and crash records, which are not considered in this paper.

1. Introduction

In recent years, the number of vehicles in China has increased rapidly. There were 138 million registered vehicles in China in 2007, and this number has increased to 214 million in 2011 (National Bureau of Statistics of China, 2012). In Beijing, this number reached 5.2 million in 2012, increasing 66.2% from 2007 (Statistical Communiqué of Beijing on the 2012 National Economy and Social Development, 2012; Statistical Communiqué of Beijing on the 2012 National Economy and Social Development, 2012). Meanwhile, traffic crashes have unfortunately caused a staggering degree of property damage as well as numerous deaths in China. In 2011, the Chinese government reported 210,312 traffic crashes (3934 in Beijing), resulting in 62,387 fatalities (924 in Beijing) and 237,421 injuries (4503 in Beijing), causing a direct economic loss of about 1.078 billion yuan (19 million yuan for Beijing) (National Bureau of Statistics of China, 2012). Traffic crash records indicated that speeding was one of the three major contributing factors (the other two being drunk driving and fatigued driving); speeding alone accounted for 14.2 percent of all traffic fatalities in 2010 (Road Traffic Crashes of China, 2010). To better address this issue, speed control devices, regarded as a potentially effective approach to reducing traffic crashes and improving safety, are installed at sites where speeding-related traffic crashes are more likely to happen.

In China, speed control devices are classified as non-intrusive, less-intrusive and intrusive speed control devices, based on the decelerating capability (Zheng, 2007). The speed reduction marking (SRM) is one kind of non-intrusive speed control device which is used extensively on highways and urban expressways because it is not only capable of warning drivers to slow down, but it has less negative effects on drivers and vehicles as well. In Beijing in particular, SRMs are mainly used in downhill sections of urban expressways.

According to the Chinese national standard road traffic signs and markings (GB5768–2009), SRMs, which are classified into longitudinal speed reduction markings (LSRMs) and transverse

* Corresponding author. Tel.: +86 13911395560.
E-mail addresses: dinghan86@hotmail.com (H. Ding), zhaoxiaohua@bjut.edu.cn (X. Zhao), jrong@bjut.edu.cn (J. Rong), jianming.ma@txdot.gov (J. Ma).

http://dx.doi.org/10.1016/j.aap.2014.11.018
0001-4575/

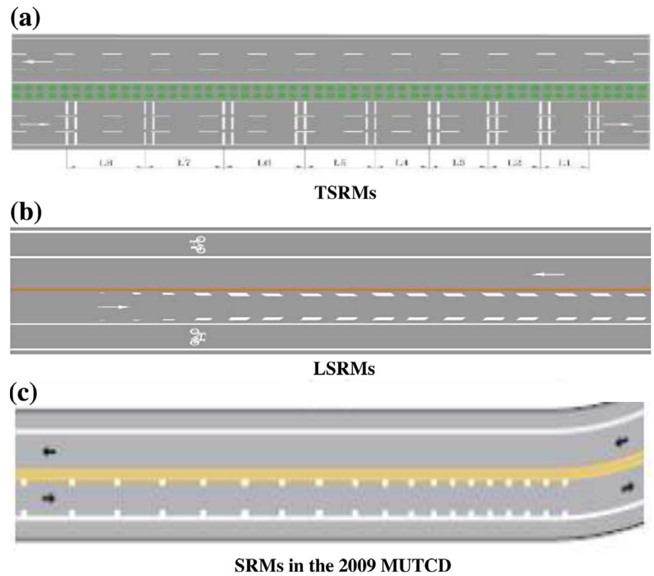

Fig. 1. SRMs in China (Standardization Administration of the People's Republic of China, 2009) and the U.S. (Federal Highway Administration, 2009). (a) TSRMs; (b) LSRMs and (c) SRMs in the 2009 MUTCD.

speed reduction markings (TSRMs), are placed on or in advance of horizontal or vertical curves, tunnels, or other road features where drivers need to slow down in advance (see Fig. 1(a) and (b)). Although installation principles and design parameters have been determined to some degree (Standardization Administration of the People's Republic of China, 2009), there is still a lack of more detailed regulations that correspond to different road conditions. In other words, in the national standard it is unclear which kind of SRMs should be used based on specific conditions; therefore their current design and management operations may not be economical and effective.

Details regarding the design, application, placement, guidance, options and support provisions for SRMs can also be found in the U. S. 2009 Manual on Uniform Traffic Control Devices (the 2009 MUTCD). According to the 2009 MUTCD, SRMs (see Fig. 1(c)) are transverse markings which are placed on the roadway within a lane (along both edges of the lane) in a pattern of progressively reduced spacing to create the illusion that drivers are driving faster than they really are, thus persuading them to slow down (Federal Highway Administration, 2009). Nevertheless, because of the differences in some aspects (such as patterns, placement locations, and so on) between Chinese and American standards, the design and management of SRMs in China cannot be directly translated or transferred from other countries.

Therefore, the objective of this paper is to study the effectiveness and adaptability of SRMs in downhill sections of urban roads through empirical research. According to the conclusions, the authors would like to propose theoretical recommendations for design and placement locations related to downhill sections on urban roads to supplement the national standard in China. In addition, such guidelines can also be provided to road designers, traffic engineers, and government agencies.

2. Literature review

Focusing on the effectiveness and adaptability of SRMs as speed control devices, significant research had been conducted in China as well as in other countries.

Meyer (1999) examined whether optical speed bars could reduce speed and speed variation in highway work zones. The pattern and function of optical speed bars was similar to the SRMs regulated in the 2009 MUTCD. The impact of optical speed bars on drivers' speed was investigated along with the underlying mechanism and the usefulness of the technique in work zones. By creating simulations of various types of optical speed bars, subjective evaluations of the relative effectiveness were acquired. The research reached the conclusion that optical speed bars caused a small reduction in both speed and speed variation due to their warning and perceptual effects.

Gates et al. (2008) explored the effectiveness of experimental transverse-bar pavement markings – a speed-reduction treatment – on freeway curves. Using vehicle speed as an indicator, a before-and-after analysis was performed to determine the short-and long-term effectiveness of an experimental transverse-bar pavement marking treatment. The results of analysis of variance (ANOVA) indicated that curve speeds were effectively reduced, especially shortly after installation of the experimental transverse pavement marking treatment.

Katz (2007) evaluated the effectiveness of peripheral transverse lines. Conducting research in the field, in a simulator, and in a controlled research setting, respectively, the researcher determined the effectiveness and optimal design of peripheral transverse markings. In the field study, the research concluded that pavement markings could reduce vehicle speeds up to 59% in the short term and 24% in the long term, as compared with a placebo. However, after the simulator study, the research encountered a large degree of variability in vehicle speed, which made the simulator ineffective at comparing designs. Finally, on a controlled freeway ramp type of curve, speed reductions resulting from treatments were 42% greater than the reduction with a placebo.

Zhang et al. (2008) studied the impacts of road humps on driving comfort and safety. In a field test, speed and acceleration data were collected in order to observe the relationship between vehicles' travel speeds and body acceleration as well as axis acceleration while vehicles were driving through the humps with different configuration dimensions. Results showed that the height of the hump had a direct relationship to speed-control, contrary to the effect of the width of the hump.

Wang et al. (2009) observed the effectiveness of vibratory speed reduction bars in reducing speed by recording the velocities of vehicles traveling through vibratory speed reduction bars. It was concluded that passenger cars had a greater speed reduction than heavy vehicles.

Jiang et al. (2010) discussed the effectiveness and adaptability of typical speed control devices, including speed limit signs, rumble strips and speed bumpers, according to the empirical data collected on real roads. The results showed that speed bumpers were the most effective in reducing speeds and speed limit signs were the least effective, whereas the speed limit signs had the most long-lasting effect. In terms of adaptability, speed limit signs rendered the lowest level of tension and discomfort; speed bumpers resulted in the highest level, adversely affecting tension and discomfort.

To summarize, there is a lack of research that examines the effectiveness and adaptability of SRMs in downhill sections of urban road overseas, and much less research in China as well. Furthermore, existing research to evaluate the effectiveness of SRMs has usually been performed through field studies, so that relatively adequate data and results could be acquired in real road and traffic conditions. Nevertheless, simulation study can minimize the compounding influences of complicated road and traffic conditions, allowing the exploration of the effects of SRMs alone in reducing speed. Therefore, this paper will research the effectiveness and adaptability of SRMs in downhill sections of urban roads based on a driving simulation study.