

Impact of Uneven Lighting Environments on Guide Sign Visibility in Interchange Areas of Road Tunnels: A Study of Bright-to-Dark Transitions in Diverging Area

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Abstract

To investigate the impact of “bright to dark” uneven lighting conditions on driver recognition of retroreflective guide signs in the diverging zones of underwater ramp interchanges, this study adjusts the luminance contrast between adjacent lighting segments in a tunnel to explore its effect on the recognition distance of retroreflective guide signs, thereby providing a basis for the rational design of lighting conditions in this area. Based on the driver’s safe recognition process, the minimum sight distance requirements for retroreflective guide signs were first determined under three representative operating speeds. Following the tunnel lighting design principles specified in Chinese standards, eight

dark-environment luminance levels and nineteen bright-environment luminance levels were established. A total of 124 non-uniform “bright–dark” lighting combinations were then generated by varying the luminance difference in 1 cd/m² increments. Subsequently, 24 passenger car drivers were selected to conduct dynamic recognition experiments of guide signs under the “bright–dark” lighting transition conditions in the tunnel ramp diverging zone. Recognition distances were measured using a non-contact speedometer to capture the driver’s distance to the sign. A regression model was developed to quantify the relationship between sign recognition distance, luminance difference, and dark-environment luminance. The model’s accuracy is reflected in the fact that 92.7% of the predicted values had an absolute error of less than 10 m compared to the observed values. The results show that luminance difference has a significant impact on recognition distance, which increases initially and then stabilizes as luminance difference grows. When the dark-environment luminance is below 3.5 cd/m², the effect of luminance difference on recognition distance is more pronounced than when it exceeds 3.5 cd/m². Based on these findings, threshold values of bright-environment luminance ensuring safe recognition distances under varying dark-environment luminance conditions are proposed. It is further recommended that, for design speeds of 100 km/h or higher, the dark-environment luminance should not be lower than 2.5 cd/m² to maintain safe visibility of retroreflective guide signs.

Keywords: tunnel light environment; non-uniform light environment; diverging area of interchange ramp in underwater tunnels; retroreflective guide sign; real vehicle experiment; safe visual recognition requirement

1. Introduction

In regions characterized by high mountains, deep valleys, and turbulent waterways—where the terrain is environmentally sensitive, complex, and unsuitable for direct road construction—tunnels provide an adaptive and environmentally friendly solution. They can effectively mitigate the influence of topography and climate on traffic flow, thereby improving driving safety and operational efficiency. With the continuous growth of transportation demand, tunnels have increasingly become integrated with interchanges and ramps, forming multidimensional transportation structures that optimize spatial utilization. Examples such as the Tiger Leaping Gorge Tunnel in Yunnan and the Shen-Zhong Subsea Tunnel in Guangdong demonstrate the application of traffic diversion within tunnel structures. Such integrated designs enable grade separation of traffic, enhancing overall traffic flow efficiency.