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Before–After Evaluation of a Pacemaker System in a Highway Tunnel Using Spatiotemporal Traffic Flow Patterns and Fundamental Diagram Analysis

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Abstract

In this study, the traffic operational effects of a pacemaker system (PMS) on the traffic operation in the Geumnam Tunnel on the Seoul–Yangyang Expressway was evaluated herein using a before–after analysis based on long-term vehicle detection system (VDS) data. Changes in spatiotemporal traffic flow and traffic capacity, and speed improvement under different levels of service (LOS) were analyzed using data from five VDS detectors installed upstream and downstream of the tunnel. After PMS installation, (i) increased average and 25th-percentile speeds at most detector locations and decreased standard deviation of speed were observed both near the tunnel exit and the downstream sections, (ii) maximum traffic volume was increased from 1661 to 1765 veh/h/lane (~6.3% increase), (iii) LOS-based speed improvement analysis showed that mean speed and 25th-percentile speed increased by ~6.5%, indicating the alleviation of speed reduction among low-speed vehicles due to PMS. These results prove that PMS increases vehicle speed, reduces speed variability, and enhances traffic flow stability and processing capability. These findings provide empirical evidence supporting the operational effectiveness of a PMS as a practical tool for mitigating phantom congestion in highway tunnel sections and reducing the speed differences between vehicles and improve traffic stream stability.

Keywords: pacemaker system; tunnel; phantom congestion; spatiotemporal traffic flow analysis; traffic capacity

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1. Introduction

Traffic congestion in highway tunnels is a critical issue because it reduces their operational efficiency and increases crash risk. In particular, phantom congestion often occurs in tunnel sections even in the absence of physical bottlenecks. This type of congestion is usually triggered by unconscious deceleration, speed differences between vehicles, and delayed driver response in a confined environment. As a result, traffic flow in tunnel sections is more vulnerable to instability than that in ordinary freeway segments. The operating environment of traffic in tunnels differs from that in open-road freeway sections. Drivers are exposed to a closed space, limited visual cues, and abrupt changes in lighting and alignment. These conditions can induce psychological pressure and speed reduction, especially near tunnel entrances and in upgrade sections. Even a small disturbance can propagate downstream and develop into unstable traffic flow. Such instability reduces the average speed of vehicles, increases their speed variability, and can eventually increase the likelihood of recurring congestion and rear-end collisions.

To improve traffic operation in tunnels, effective countermeasures are needed to suppress unnecessary speed reduction and stabilize the traffic flow. Among the available operational strategies, the pacemaker system (PMS) has been introduced as a practical measure for mitigating phantom congestion in the tunnel sections of roads. The PMS sequentially illuminates LED guidance lights in the direction of travel to induce drivers to maintain uniform speed of their vehicle. The expected role of a PMS is not limited to only increasing the vehicle speed. It is also intended to reduce the speed differences between vehicles and improve the stability of the traffic stream. In Korea, the PMS has been applied in several tunnel sections as a part of the practical freeway traffic management efforts. Its operational effects, however, should be evaluated using empirical traffic data. In particular, it is necessary to determine whether the PMS improves the traffic flow not only at a single detector location but also over space and time, whether it affects the maximum traffic volume that can be accommodated in the tunnel section, and whether its effects vary depending on the traffic conditions.

The aim of this study was to quantitatively evaluate the effect of a PMS on the traffic flow in the Geumnam Tunnel on the Seoul–Yangyang Expressway using a before–after analysis based on long-term vehicle detection system (VDS) data. A PMS was installed and operated in the tunnel from December 19, 2021 to January 28, 2022. The analysis used data from five VDS detectors installed upstream and downstream of the tunnel, including those from the detector located at the tunnel exit. The pre-PMS period was defined to be from December 1, 2020 to November 30, 2021, and the post-PMS period from February 1, 2022 to January 31, 2023. Data collected during the installation period were excluded from the analysis.

The effect of the PMS was evaluated from three perspectives. First, a spatiotemporal traffic flow analysis was conducted using five VDS detectors to examine the changes in the average speed, 25th-percentile speed, and the standard deviation of speed before and after PMS installation. Second, a traffic capacity analysis was performed using the Greenshields model to estimate changes in the maximum traffic volume based on the speed–flow relationship. Third, a before–after speed improvement analysis was performed by considering different levels of service (LOS) to examine whether the observed in the speeds of the vehicles was statistically significant or not.

The remainder of this paper is organized as follows: Section 2 reviews the previous studies related to traffic operation in tunnels and PMS. Section 3 describes the data preparation and analysis methods used in this study. Section 4 presents the results of the analyses. Section 5 summarizes the major findings of this study and discusses future research directions.

2. Literature Review

2.1. Changes in the Visual Environment in the Tunnel Sections and Speed Behavior of Drivers

Tunnel sections have visual and spatial characteristics that differ from those of open-road segments, and these characteristics directly affect driver behavior and traffic flow stability. Because tunnels are semi-enclosed environments with limited sight distance, drivers experience abrupt environmental transitions at the entrance and within the interior section. In particular, at the tunnel entrance, drivers move suddenly from a bright external environment to a relatively dark interior environment. This transition increases visual adaptation time and cognitive workload, which may lead to speed reduction and unstable driving behavior. Qin et al. reported, based on field experiments in an actual highway tunnel, that pupil size and fixation characteristics changed markedly when drivers entered the tunnel and that these changes were significantly related to vehicle speed [1]. Similar findings were also reported by Fu et al. and Hu et al., who showed that tunnel entrance conditions and spatial visual characteristics affected drivers' visual responses and speed adjustment behavior [2,3].

Because tunnels are enclosed environments, they may increase drivers' visual fatigue, reduce cognitive performance, and intensify psychological pressure, thereby increasing crash risk. For this reason, a variety of safety facilities have been introduced to improve traffic safety in tunnel sections, and recent studies have increasingly attempted to empirically identify how such facilities influence driver behavior and traffic flow. Ru et al. analyzed the effects of tunnel safety facilities on vehicle speed control using the Analytic Hierarchy Process (AHP) [4]. Their study focused on strobe lights and LED information signs and reported that strobe lights were effective in attracting drivers' visual attention, whereas LED information signs supported speed control by inducing appropriate driver responses. The study further suggested that the combined installation of the two facilities could improve both safety and operational efficiency compared with the use of a single facility. Chen et al. also examined the optimization of tunnel safety facilities based on drivers' visual perception and reported that conventional facilities, such as flashing lights and contour markings, directly affected drivers' field of view and responsiveness [5]. In addition, the study showed that detailed design factors, including lighting color, spacing, and flashing interval, were closely related to crash prevention performance.

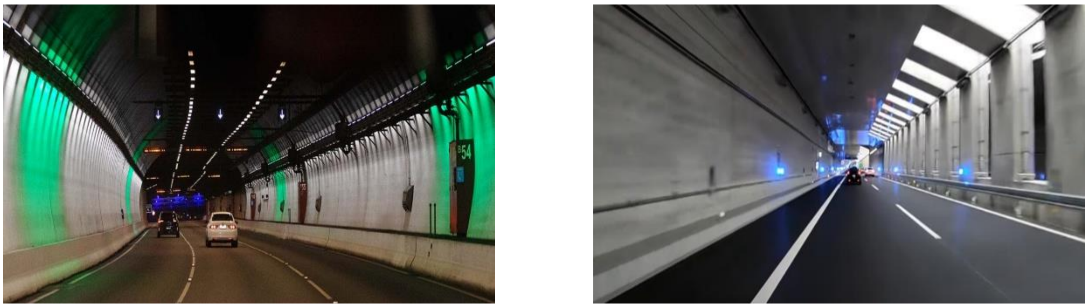
To mitigate these problems, previous studies have examined visual guidance facilities and visual intervention devices in tunnel environments. Ozturk et al., using a driving simulator, analyzed the effects of different tunnel lighting scenarios on drivers' lane-changing behavior [6]. Their results showed that red and flashing lights were effective in inducing hazard recognition and safe deceleration and lane-changing behavior, whereas green lighting tended to increase driving speed by signaling that the risk had been resolved. Wang et al. showed that reverse-perspective-illusion deceleration lines and visual-intervention deceleration devices in a long downhill tunnel reduced both average speed and speed standard deviation [7]. The study further reported that a 60 m reverse-perspective-illusion deceleration line and a 90° fold-line visual-intervention device produced the most distinct effects on speed reduction and speed dispersion. Similarly, Zheng et al. proposed a rhythm-based visual reference system to improve the monotonous visual environment of long highway tunnels [8]. Their results showed that rhythm-based visual markings improved the accuracy of speed judgment and reduced driver reaction time, with multicolor markings being more effective than monochrome markings.

In addition, Zhang proposed a quantitative method for evaluating the safety of the tunnel visual environment [9]. The study comprehensively considered visual factors such as illuminance, luminance uniformity, color temperature, and contrast ratio, and examined how they affected sight distance, visual adaptation time, and lane recognition. This work is meaningful in that it moved beyond subjective assessment and provided an empirical basis for improving tunnel lighting and visual environments through quantitative verification. More recently, cognitive issues in curved and spiral tunnels have also attracted attention. Xia et al. reported that drivers in spiral tunnels tend to underestimate roadway curvature and that elements with visual reference functions play an important role in driver cognition [10].

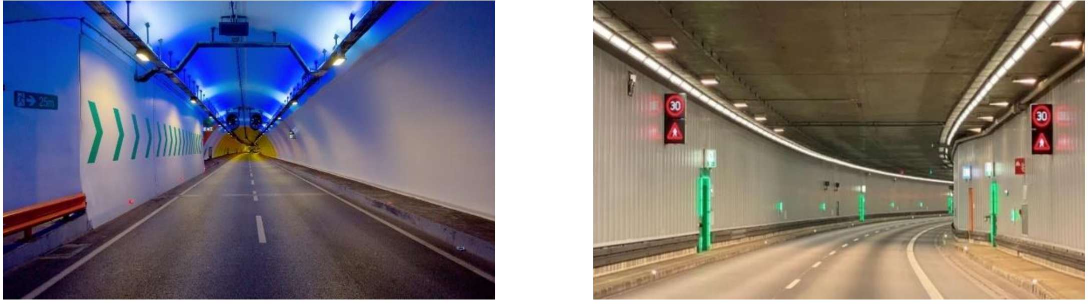
2.2. Speed Guidance Strategies in Tunnel Sections and Application of PMS

Various operational measures have been introduced to mitigate unstable traffic flow in tunnel sections of roads by providing visual guidance and supporting speed recovery. Phantom jams in tunnels refer to congestion that occurs spontaneously through the amplification of small perturbations in the traffic flow, even in the absence of obvious physical bottlenecks, such as vehicle crashes, roadworks, or lane closures. Suijs et al. defined phantom jams as congestion that occurs under metastable traffic conditions without a physical bottleneck and argued that preventing such congestion requires either reducing the perturbation itself or mitigating the instability of traffic flow [11].

In this context, the PMS is an operational strategy that provides drivers with visual speed cues aligned with their direction of travel and induces them to maintain uniform speed. A PMS is particularly applicable to tunnel sections where drivers tend to decelerate unconsciously, such as upgrade segments and areas near the tunnel exits. International applications have demonstrated the practical use of the PMS or similar systems in tunnel environments. In Melbourne, Australia, a green LED-based dynamic visual guidance system was installed in the Burnley Tunnel and its operational reports indicated increase in the travel speed and substantial reduction in recovery time during peak periods. In Japan, a PMS was introduced on the C3 Gaikan Expressway to suppress unconscious deceleration on upgrade sections and support speed recovery. In Istanbul, Türkiye, the Eurasia Tunnel introduced a PMS in 2020 using arch-shaped LED lighting that sequentially illuminated in the direction of traffic flow and guided drivers to maintain a target speed. Similar PMS installation has also been reported in tunnels on the Austrian A9 motorway. Representative examples of PMS implementation are shown in Figure 1.



(a) Burnley Tunnel **(b)** C3 Gaikan Expressway



(c) Eurasia Tunnel **(d)** A9 Pyhrn Autobahn

Figure 1. Examples of PMS implementation in tunnel sections in different countries.

These international cases suggest that a PMS is not merely a visual facility but an operational strategy intended to mitigate phantom jams and promote speed harmonization in tunnel sections. They also suggest that the expected effects of a PMS are not limited to an average speed increase, but can extend to speed recovery, smooth traffic flow, and improved operational stability. However, most existing evidence has been presented as case descriptions or operational reports, and quantitative detector-based evaluations remain limited.

2.3. *Analytical Approaches for Evaluating the Effects of Operational Strategies on Traffic Flow*

A single-point comparison of average speed is not sufficient for evaluating the effects of traffic operational strategies in tunnel sections. Measures such as the PMS are intended not only to increase speed at a specific location, but also to stabilize traffic flow, reduce speed dispersion, and improve traffic operation over space and time. Therefore, the operational effects of such strategies should be examined using a broader analytical framework that includes before–after evaluation, spatiotemporal traffic flow analysis, and macroscopic capacity assessment.

The most basic framework for empirically evaluating an operational strategy is the before–after study. The FHWA Highway Safety Improvement Program (HSIP) Evaluation Guide emphasizes that evaluation should verify whether an implemented measure has produced meaningful effects and should support future decision-making [12]. It also distinguishes project, countermeasure, and program-level evaluations, and highlights that the choice of measures of effectiveness, analysis period, and data structure should depend on the evaluation objective. This perspective implies that the evaluation of PMS should not be limited to average speed, but should also consider multiple indicators such as speed variability, operational condition, and traffic processing capability. In addition, before–after studies require careful consideration of study period, data structure, and potential sources of bias. Persaud and Lyon pointed out that simple before–after comparisons may be affected by regression-to-the-mean, traffic volume changes, and temporal trends, and argued that observational evaluations should be designed carefully to improve validity [13]. Although their discussion focused on safety evaluations, the same concern is relevant when interpreting operational before–after comparisons based on detector data.

The effects of an operational strategy such as PMS should also be interpreted through spatiotemporal traffic patterns rather than through data from a single detector. Treiber and Helbing proposed the adaptive smoothing method to reconstruct spatiotemporal traffic dynamics from stationary detector data [14]. Their method accounts for the fact that the propagation direction of information differs between free-flow and congested-flow conditions and enables speed, flow, and other traffic variables to be reconstructed as continuous functions of space and time. They further showed that this approach is useful for traffic state visualization, reconstruction from incomplete information, rapid identification of traffic breakdowns, and verification of traffic models. This analytical perspective is directly related to the present study, in which multiple VDS datasets are used to generate contour maps of average speed, 25th-percentile speed, and speed standard deviation. In this sense, spatiotemporal reconstruction provides a useful way to identify whether the effect of PMS is confined to the tunnel interior or propagates to adjacent upstream and downstream sections.

In addition to spatial and temporal patterns, the structural effect of an operational strategy should be assessed using the speed–flow relationship and the resulting change in maximum traffic volume. Greenshields et al. observed that average speed decreases as congestion increases and that traffic volume does not continue to increase beyond a certain level [15]. Their work described roadway working capacity based on the relationship among speed, density, and flow and became the foundation of subsequent fundamental-diagram-based traffic flow analysis. More recent studies have continued to emphasize that capacity analysis is essential for understanding congestion and infrastructure performance. For example, Odiakose and Iyeke evaluated traffic congestion using the volume-to-capacity ratio and the speed performance index, showing that congestion analysis should jointly consider operational speed and roadway capacity [16]. Similarly, Cui emphasized that traffic flow forecasting and capacity analysis are fundamental tools for identifying bottlenecks and improving traffic system performance [17,18]. These studies support the view that an operational strategy should be evaluated not only in terms of speed increase, but also in terms of whether it improves the ability of the roadway to process demand under stable conditions. If PMS reduces unconscious deceleration and promotes speed harmonization in a tunnel, its effect may appear not only as an increase in average speed but also as an upward shift in the speed–flow relationship or an increase in the maximum traffic volume.

Recent traffic flow studies also suggest that flow stability and speed homogeneity are important evaluation dimensions. Li et al. showed that traffic stability and capacity are closely related and that changes in driving behavior can alter both the unstable region of traffic flow and the attainable capacity [19]. Zheng et al. further reported that coordinated variable speed limit control can improve average speed and speed homogeneity while maintaining smoother freeway traffic flow across consecutive bottlenecks [20]. Although these studies did not examine PMS directly, they provide an important implication for PMS evaluation: if a tunnel-based speed guidance system is effective, its benefit should be reflected not only in higher speed but also in reduced speed dispersion, smoother traffic flow, and improved macroscopic performance.

2.4. Research Opportunities

From previous studies, it has been found that the visual environment in tunnel sections affects the perception of drivers, speed behavior of vehicles, and traffic flow stability. In addition, previous studies have shown that visual guidance devices and speed harmonization strategies can improve speed control and mitigate unstable traffic flow in tunnels. Therefore, it is necessary to evaluate the effects of visual speed guidance systems in actual traffic conditions. Although a large number of studies on visual environments in tunnels and phantom jam mitigation have been performed to date, less effort has been devoted to quantitatively evaluating the effects of a continuously applied PMS using long-term detector data. In particular, limited attention has been paid to integrated evaluations that consider the changes in the spatiotemporal traffic flow, speed distribution characteristics, and changes in the traffic capacity together. Most previous studies have focused on driver responses, experimental findings, or qualitative operational outcomes.

Unlike past studies, this study attempted to evaluate the effect of a PMS from the perspective of traffic operations using long-term VDS data collected before and after PMS implementation. The analysis considers the changes in the spatiotemporal traffic flow and traffic capacity based on the speed–flow relationship, and also the improvement in the vehicle speed under different LOS conditions. This framework is useful for providing empirical evidence on the operational effectiveness of a PMS and for supporting future traffic management and deployment strategies in tunnels.

3. Methodology

The analysis framework proposed in this study is illustrated in Figure 2. The analysis consisted of three components: analysis of the spatiotemporal traffic flow, traffic capacity, and before–after speed improvement.

Firstly, an analysis of the spatiotemporal traffic flow was performed to examine the variation in the traffic conditions over space and time after PMS implementation. Data from five VDS detectors installed upstream and downstream of the Geumnam Tunnel were used for analyzing the changes in the average and 25th-percentile speeds, and the standard deviation of speed. Secondly, an analysis of the traffic capacity was done to estimate the change in the maximum traffic volume before and after PMS installation based on the speed–flow relationship. This analysis intended to determine whether the PMS improved the traffic processing capability of the tunnel section or not. Finally, a before–after speed improvement analysis was performed to compare the average and 25th-percentile speeds of vehicles under different LOS and statistically test whether the observed changes were significant or not.

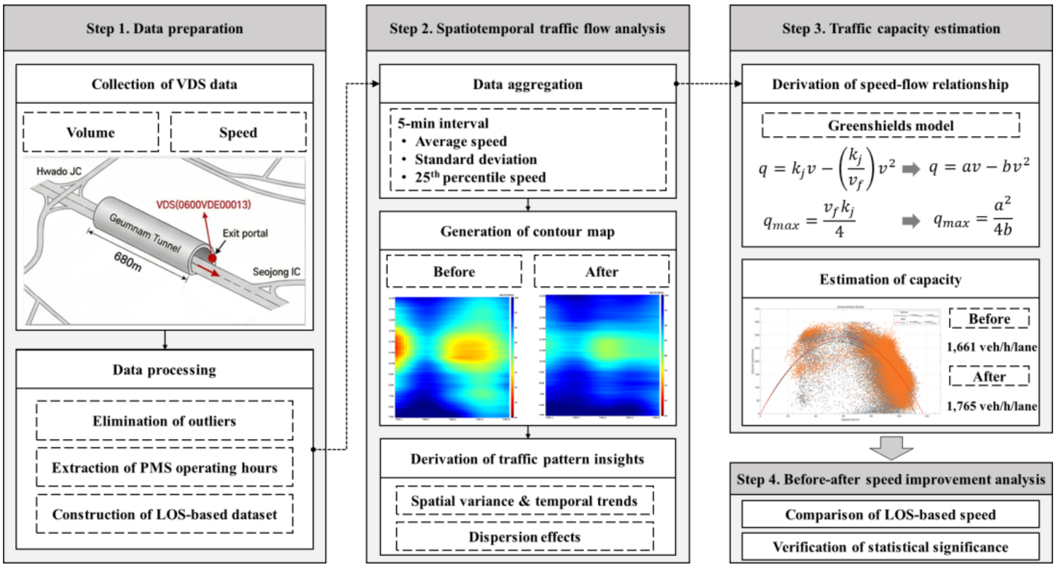
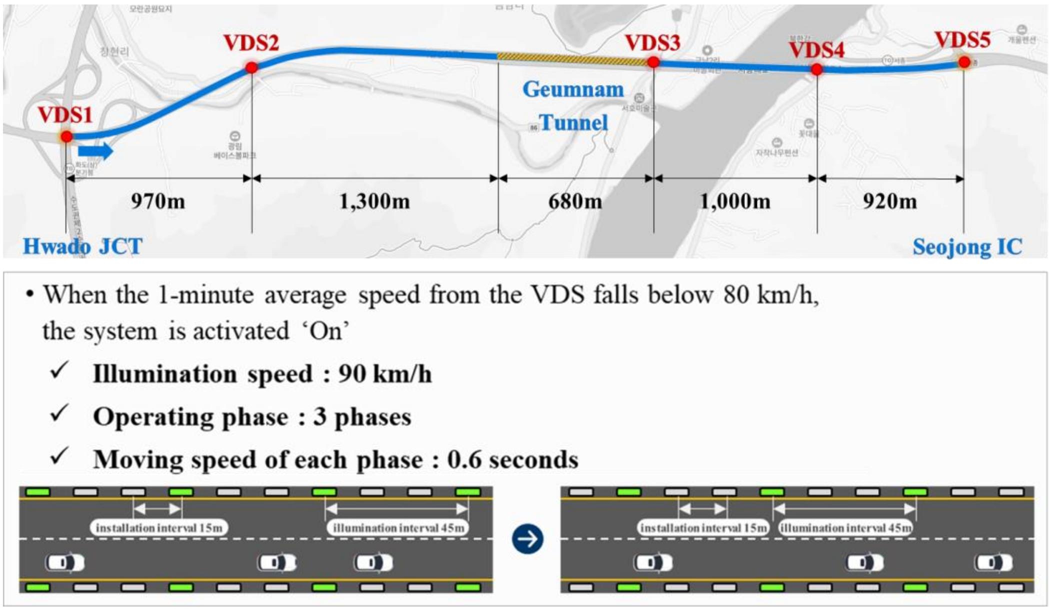


Figure 2. Schematic showing the analysis framework employed in this study for investigating the effect of PMS implementation on traffic flow.

3.1. Data Preparation

The Geumnam Tunnel on the Seoul–Yangyang Expressway between Hwado JCT and Seojong IC was chosen as the study area (Figure 3). It is a two-lane unidirectional tunnel with a length of 680 m. The minimum and maximum speed limits for passenger vehicles are 50 and 100 km/h, respectively. A PMS was installed and operated from December 19, 2021 to January 28, 2022. A total of 90 LED guidance lights were installed inside the tunnel, with 45 units on each side at intervals of approximately 15 m. The PMS sequentially illuminates the LED guidance lights in the direction of travel to induce uniform driving speeds.



- When the 1-minute average speed from the VDS falls below 80 km/h, the system is activated 'On'
  - ✓ **Illumination speed : 90 km/h**
  - ✓ **Operating phase : 3 phases**
  - ✓ **Moving speed of each phase : 0.6 seconds**

Figure 3. Schematic showing the Geumnam Tunnel on the Seoul–Yangyang Expressway that was the study area and the details of the PMS installed in this tunnel.

Data from five VDS detectors installed upstream and downstream of the tunnel, including the detector located near the tunnel exit, were used in this study. These data were used to examine the direct effect of the PMS on one segment of the tunnel and its spatial influence on adjacent segments. The analysis aimed to determine whether the changes in the traffic flow associated with PMS implementation were confined to the interior of the tunnel or propagated to the upstream and downstream sections.

A 5 min aggregated traffic volume and speed data collected from the VDS detectors were used in this study. The period before PMS implementation was from December 1, 2020 to November 30, 2021 and that after PMS implementation was from February 1, 2022 to January 31, 2023. Data collected during the PMS installation period, from December 19, 2021 to January 28, 2022, were excluded. This period setting ensured a consistent comparison between the pre- and post-PMS implementation using datasets of equal duration.

The collected data were preprocessed as follows. First, data with speed values less than zero were treated as outliers and removed. Second, periods likely to deviate from ordinary traffic patterns, such as national holidays and summer vacation season, were excluded. Third, the PMS operation log was reviewed, and only the time periods during which the system was actively operated were extracted. The PMS was found to operate mainly from 5:00 A.M. to 4:00 P.M. and the analysis was conducted using data from this time period. Although long-term VDS data were used to reduce the effect of short-term external factors, complete control by eliminating the effects of external variables such as weather, accidents, and seasonal effects was not possible. Nevertheless, the analysis ensured consistency by comparing long-term data collected from the same section under the same detector system.

Because the effect of PMS can vary with traffic congestion, the pre- and post-PMS datasets were further classified by the level of service (LOS). This classification was determined based on the Korean Highway Capacity Manual for a two-lane roadway with a design speed of 100 km/h (Table 1). Since the Geumnam Tunnel has a longitudinal grade of 0.55%, which is close to level terrain, the LOS thresholds were estimated by applying a heavy-vehicle adjustment factor of 0.96, reflecting a traffic composition of 95.4% passenger cars, 0.9% medium-sized vehicles, and 3.7% heavy vehicles. Accordingly, based on the traffic volume levels, a classification of conditions LOS A–F was done and the pre- and post-PMS datasets were organized under each LOS condition (Table 2). These LOS-based datasets were subsequently used for speed comparison and statistical tests.

Table 1. Traffic volume criteria for different LOS conditions.

LOS		Traffic Flow Condition	Design Speed, 100 kph		
			Volume (pc/h/lane)	Volume (pc/5min/lane)	Volume (veh/5min/2lane)
A	Free Flow	Very high degree of freedom in speed selection and directional maneuvers	≤ 600	≤ 50	≤ 96
B	Stable Flow	High degree of freedom in speed selection, but traffic freedom is lower than A	≤ 1,000	≤ 83	≤ 159
C	Stable Flow	Speed selection is influenced by the presence of other vehicles	≤ 1,350	≤ 113	≤ 217
D	Stable Flow at Low Density	Both speed and directional maneuver freedom are considerably restricted	≤ 1,750	≤ 146	≤ 280
E	Unstable Flow	Speed and directional maneuver freedom are severely restricted	≤ 2,200	≤ 183	≤ 351
F	Capacity (Breakdown Condition)	Exceeds capacity; road function is nearly lost	-	-	-

Table 2. Number of observation datasets before and after PMS implementation for different LOS conditions.

LOS		Before	After
A	Free Flow	7,546	3,538
B	Stable Flow	13,291	9,350
C	Stable Flow	8,755	7,161
D	Stable Flow at Low Density	6,973	6,494
E	Unstable Flow	1,920	1,531
F	Capacity (Breakdown Condition)	4,172	2,633

3.2. Analysis of the Spatiotemporal Traffic Flow

This section presents the method used for analyzing the spatiotemporal characteristics of traffic flow before and after PMS implementation. Since a PMS is intended to reduce the speed differences between vehicles and induce uniform driving behavior, its operational effects cannot be fully explained using data from a single detector. Thus, data from five VDS detectors installed upstream and downstream of the Geumnam Tunnel was used in this study. For the spatiotemporal traffic flow analysis, the location of each VDS detector was defined as the spatial axis, x, and the observation time was defined as the temporal axis, t. The traffic characteristics at each location and time were represented as a function, $F(x,t)$. Three indicators were considered. First, the average speed was defined as the arithmetic mean of vehicle speeds observed at a given VDS location during a 5 min interval and was used for evaluating the overall speed level before and after PMS implementation. Second, the 25th-percentile of the speed distribution was derived. This measure captured the behavior of low-speed vehicles, which could not be sufficiently described by the average speed alone. This parameter was used to assess whether the PMS mitigated unconscious deceleration among slower vehicles or not. Third, the standard deviation of speed was used as an indicator of its variability. A low standard deviation indicated smaller speed differences between vehicles, and thus, improved traffic flow stability. Each indicator was calculated using 5 min aggregated data from each VDS detector and arranged into a spatiotemporal matrix. Contour maps were then generated for the average and 25th-percentile speeds, and the standard deviation of speed under pre- and post-PMS conditions. These maps visualize the characteristics of traffic flow as continuous spatiotemporal distributions and help identify when and where PMS-induced changes were concentrated.

To quantify the effect of PMS on traffic flow, the difference between each indicator before and after PMS operation was calculated as follows:

$$\Delta F(x,t) = F_{after}(x,t) - F_{before}(x,t) \tag{1}$$

where $F(x,t)$ denotes the average speed, 25th-percentile speed, or the standard deviation of speed. For the average and 25th-percentile speeds, a positive value of $\Delta F(x,t)$ indicates improved traffic operation. For the standard deviation of speed, a negative value indicates improved traffic flow stability.

3.3. Analysis of the Traffic Capacity of the Tunnel

This section presents the method used for evaluating the effect of PMS on the traffic processing capability of the tunnel. One of the primary purposes of PMS is to reduce unconscious deceleration and mitigate phantom congestion in tunnels. If these effects are achieved, PMS is expected to improve not only the vehicle speed but also the maximum traffic volume that can be accommodated under stable flow conditions. Therefore, this study examined traffic capacity in addition to the vehicle speed.

To this end, the speed–flow relationship before and after PMS implementation was derived using 5 min aggregated speed and traffic volume data collected from the VDS detectors. The speed–flow relationship is a representative macroscopic indicator of structural changes in the traffic flow. For estimating the maximum traffic volume, the Greenshields model was adopted. The model can be expressed as follows:

$$q = k_j v - \left(\frac{k_j}{v_f}\right) v^2 \tag{2}$$

where q is the traffic volume (veh/h), v is the average speed (km/h), k_j is the jam density (veh/km), and v_f is the free-flow speed (km/h). For convenient estimation, the equation was rewritten as

$$q = av - bv^2 \tag{3}$$

where $a = k_j$ and $b = k_j / v_f$. This reparameterized form allows straightforward curve fitting using the observed speed–flow data. The coefficients a and b were estimated separately for the pre- and post-PMS datasets. The maximum traffic volume was then obtained from the vertex of the fitted quadratic curve. Based on the Greenshields model, the maximum traffic volume can be expressed as

$$q_{max} = \frac{v_f k_j}{4} \tag{4}$$

or equivalently,

$$q_{max} = \frac{a^2}{4b} \tag{5}$$

where q_{max} denotes the traffic capacity. By comparing q_{max} before and after PMS implementation, the extent to which PMS altered the maximum traffic processing capability of the tunnel section was evaluated.

3.4. Analysis of the Before–After Speed Improvement

This section describes the method used for evaluating the speed improvement effect of the PMS using a before–after comparison. Since the PMS is designed to suppress unconscious deceleration and reduce speed differences among vehicles, its operational effects should be examined not only in

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terms of the mean speed of the vehicles but also in terms of the improvement in low-speed vehicle groups. To this end, the speed data before and after PMS installation were compared according to the LOS. The LOS classification was determined based on the traffic volume conditions and the analysis conditions were stratified to account for the possibility that the PMS effect might differ between free-flow and congested states.

Two indicators were used in this analysis. Firstly, the average speed was used as a representative measure of the speed level for each LOS condition. The difference between the average speed before and after PMS implementation was used for evaluating the overall speed improvement. Secondly, the 25th-percentile speed, which reflects the changes in the speed of low-speed vehicle groups, was used to assess the extent to which the PMS improved the speed recovery of vehicles passing through the tunnel. An increase in the average as well as 25th-percentile speeds indicates that the PMS elevated the lower end of the speed distribution and contributed to a more homogeneous traffic flow.

Descriptive statistics, namely, the mean, median, standard deviation, variance, minimum, maximum, and 25th-percentile speed values, were computed for the pre- and post-PMS datasets for each LOS condition. These measures were used to examine the direction and magnitude of changes in the vehicle speed. Subsequently, a normality test was performed. Since large-scale VDS speed data typically exhibit skewness and nonnormality, a nonparametric statistical test was applied. In particular, the Mann–Whitney U test was used to evaluate whether the differences between the average and 25th-percentile speeds between the pre- and post-PMS conditions were statistically significant or not.

4. Results

4.1. Results of the Spatiotemporal Traffic Flow Analysis

The changes in the average speed, 25th-percentile speed, and the standard deviation of speed were compared using the data from five VDS detectors installed upstream and downstream of the Geumnam Tunnel before and after PMS implementation. VDS3 was located at the tunnel exit, whereas VDS1 and VDS2 represented the upstream section and VDS4 and VDS5 represented the downstream section. The results are illustrated using contour maps, which were used to examine the spatial distribution and temporal variation in the traffic flow characteristics before and after PMS implementation.

The results for the average speed showed an overall improvement after PMS implementation. The average speed at VDS1 increased from 82.67 to 90.82 km/h, whereas that at VDS2 increased slightly from 93.20 to 94.12 km/h. At VDS3, the average speed increased from 85.23 to 89.56 km/h. The largest increase was observed at VDS4, where the average speed increased from 80.75 to 90.86 km/h. At VDS5 also, the average speed increased from 86.75 to 87.83 km/h. These results indicate that the PMS contributed to speed recovery not only within the tunnel and near the exit but also in the downstream section. The contour map of the average speed confirms that the recovery zone became more extensive after PMS implementation (Figure 4).

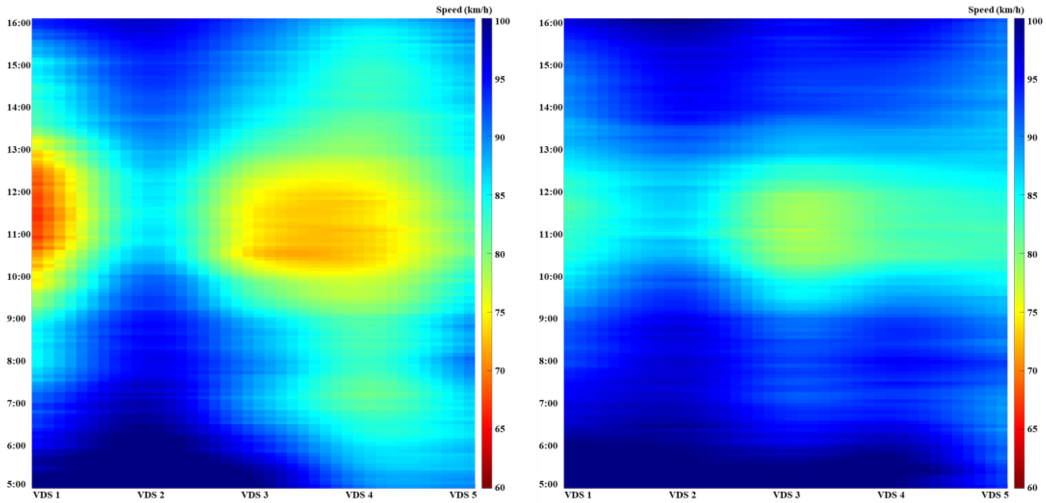

Figure 4. Contour map of the average speeds calculated from the data captured by the five VDS detectors before (left) and after (right) PMS implementation.

The results for the 25th-percentile speed showed a clearer PMS effect than those for the average speed. The 25th-percentile speed at VDS1 increased from 74.55 to 97.61 km/h, whereas that at VDS2 remained nearly unchanged, increasing from 96.17 to 96.23 km/h. At VDS3, the value increased from 82.84 to 87.59 km/h, and at VDS4, it increased from 78.43 to 88.01 km/h. At VDS5, the value increased from 83.91 to 84.91 km/h. These findings indicate that the PMS alleviated speed reduction among low-speed vehicles, particularly near and downstream of the tunnel exit. In other words, the PMS not only increased the average speed but also raised the lower end of the speed distribution. The contour map of the 25th-percentile speed supports this interpretation (Figure 5).

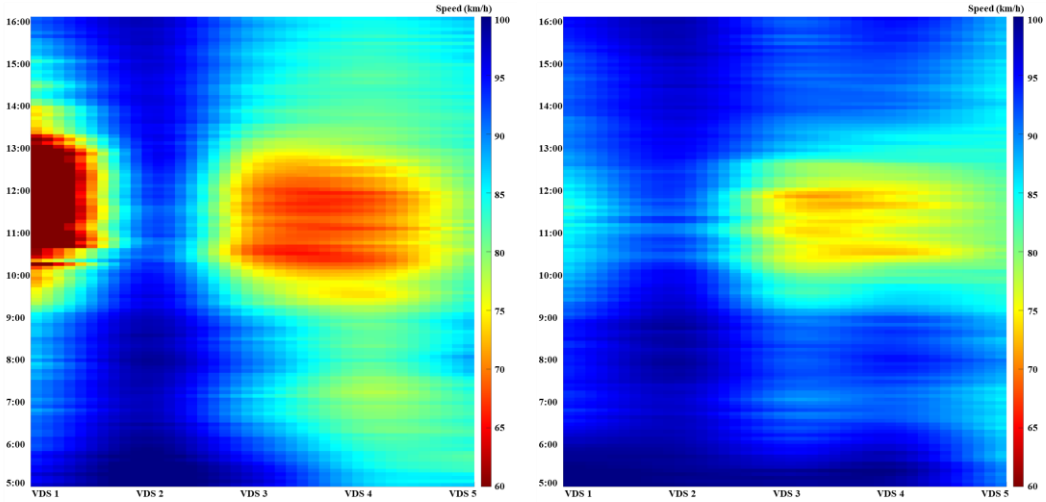

Figure 5. Contour map of the 25th-percentile speed calculated from the data captured by the five VDS detectors before (left) and after (right) PMS implementation.

The standard deviation of speed decreased at most VDS locations after PMS implementation. It decreased from 19.87 to 17.54 km/h at VDS1 and from 17.89 to 16.73 km/h at VDS2. At VDS3, the value decreased slightly from 16.56 to 16.20 km/h. At VDS4, it decreased from 12.37 to 11.02 km/h, and at VDS5, it decreased from 10.30 to 8.94 km/h. These results indicate that speed differences between the vehicles reduced after PMS implementation. They also suggest an improvement in the stability of traffic flow. The contour map of the standard deviation of speed shows that the spatial extent of highly variable traffic conditions decreased after PMS implementation (Figure 6).

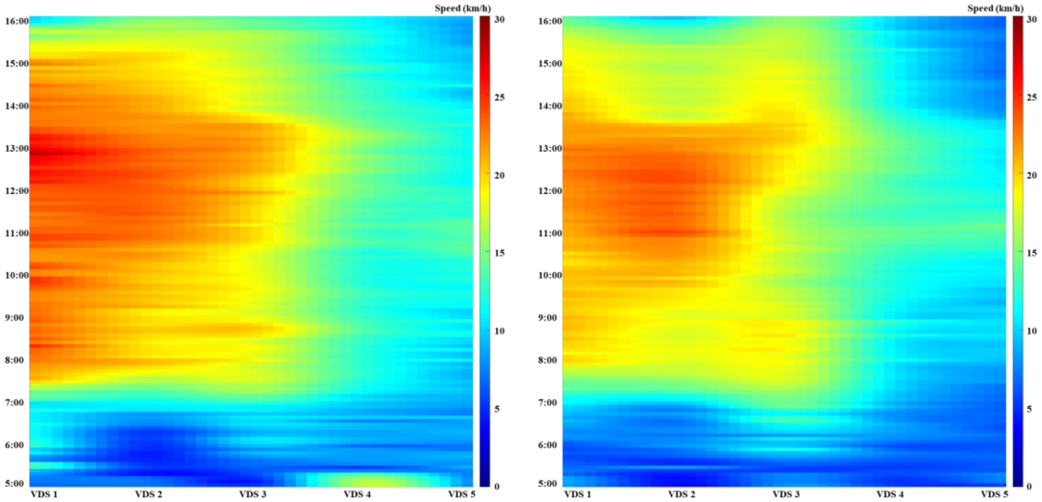

Figure 6. Contour map of the standard deviation of speed calculated from the data captured by the five VDS detectors before (left) and after (right) PMS implementation.

Further, the statistical significance of the changes in the average and 25th-percentile speeds, and the standard deviation of speed before and after PMS implementation was examined at each VDS location. As presented in Table 3, the normality test results indicated that the data for each location and indicator did not follow a normal distribution ($p < 0.05$). Therefore, the Mann–Whitney U test was applied. The results showed that the changes before and after PMS implementation were statistically significant at most VDS locations (Table 4). This indicates that the changes in the spatiotemporal traffic flow observed in the contour maps and the descriptive statistics were statistically meaningful.

Table 3. Kolmogorov-Smirnov test results for the three speed parameters before and after PMS implementation.

Classification		Average speed			Std. speed			25th %tile speed		
		Statistic	df	Sig.	Statistic	df	Sig.	Statistic	df	Sig.
VDS1	Before	0.147	133	0.000	0.240	133	0.000	0.075	133	0.064
	After	0.084	133	0.022	0.257	133	0.000	0.195	133	0.000
VDS2	Before	0.079	133	0.040	0.249	133	0.000	0.084	133	0.024
	After	0.148	133	0.000	0.161	133	0.000	0.142	133	0.000
VDS3	Before	0.126	133	0.000	0.240	133	0.000	0.157	133	0.000
	After	0.153	133	0.000	0.210	133	0.000	0.219	133	0.000
VDS4	Before	0.111	133	0.000	0.138	133	0.000	0.175	133	0.000
	After	0.124	133	0.000	0.087	133	0.016	0.165	133	0.000
VDS5	Before	0.111	133	0.000	0.133	133	0.000	0.083	133	0.025
	After	0.072	133	0.084	0.086	133	0.018	0.168	133	0.000

Table 4. Mann–Whitney U test results for the three speed parameters before and after PMS implementation.

Average speed	VDS1	VDS2	VDS3	VDS4	VDS5
Mann-Whitney U	4617.500	7596.000	5512.000	1629.000	6673.000
Wilcoxon W	13528.500	16507.000	14423.000	10540.000	15584.000
Z	−6.738	−1.990	−5.312	−11.501	−3.461
Asymp. Sig. (2-tailed)	0.000	0.047	0.000	0.000	0.001
Std. speed	VDS1	VDS2	VDS3	VDS4	VDS5
Mann-Whitney U	5030.000	7440.000	7393.000	5859.000	5673.000
Wilcoxon W	13941.000	16351.000	16304.000	14770.000	14584.000

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Z	−6.080	−2.239	−2.314	−4.759	−5.055
Asymp. Sig. (2-tailed)	0.000	0.025	0.021	0.000	0.000
25th %tile speed	VDS1	VDS2	VDS3	VDS4	VDS5
Mann-Whitney U	3306.500	8611.500	5208.500	3020.000	6796.000
Wilcoxon W	12217.500	17522.500	14119.500	11931.000	15707.000
Z	−8.828	−0.371	−5.796	−9.284	−3.265
Asymp. Sig. (2-tailed)	0.000	0.710	0.000	0.000	0.001

4.2. Results of the Traffic Capacity Analysis

This section presents the results of the traffic capacity analysis based on the speed–flow relationship before and after PMS implementation. The purpose of the PMS is to mitigate unconscious deceleration and the resulting phantom congestion in tunnel sections. Therefore, it is necessary to examine the changes in not only the vehicle speed but also in the maximum traffic volume. The speed–flow relationships before and after PMS implementation were estimated using 5 min aggregated VDS data. The fitted quadratic form was expressed as

$$q = av - bv^2 \tag{6}$$

where q is the traffic volume for a two-lane section in a 5 min interval (veh/5 min), v is the average speed (km/h), and a and b are model coefficients. The model fitting was conducted using the MATLAB Curve Fitting Toolbox and the robust fitting option based on the least absolute residual method was applied. The speed–flow relationship before PMS implementation was estimated as follows:

$$q_{before} = 9.883v - 0.088v^2 \tag{7}$$

The 95% confidence intervals of coefficients a and b were estimated to be 9.866–9.900 and 0.08801–0.08838, respectively. Based on the fitted curve, the maximum traffic volume before PMS implementation was estimated to be 276.9 veh/5 min for the two-lane section. This corresponds to approximately 1661 veh/h/lane. The speed–flow relationship after PMS implementation was estimated as follows:

$$q_{after} = 10.009v - 0.085v^2 \tag{8}$$

The 95% confidence intervals of coefficients a and b were estimated to be 9.974–10.040 and 0.08477–0.08551, respectively. The maximum traffic volume after PMS implementation was estimated to be 294.2 veh/5 min for the two-lane section, which corresponds to approximately 1765 veh/h/lane. Accordingly, the maximum traffic volume increased by 17.3 veh/5 min for the two-lane section after PMS installation. When converted to an hourly traffic volume per lane, the increase was approximately 104 veh/h/lane. This corresponds to a 6.3% increase in traffic capacity.

As shown in Figure 7, the speed–flow distributions before and after PMS implementation exhibited a typical parabolic pattern. The fitted curve after PMS implementation was located above that before its implementation. The upward shift in the vertex of the curve indicates that a relatively stable traffic condition was maintained under higher traffic demand after PMS implementation. This implies that the PMS reduced the likelihood of phantom congestion by mitigating unconscious deceleration and promoting speed harmonization within the tunnel section. Overall, the Greenshields-model-based traffic capacity analysis showed that the maximum traffic volume increased after PMS implementation. This result demonstrated that the PMS improved the operational efficiency of vehicles in the tunnel by mitigating phantom congestion and inducing stable traffic flow.

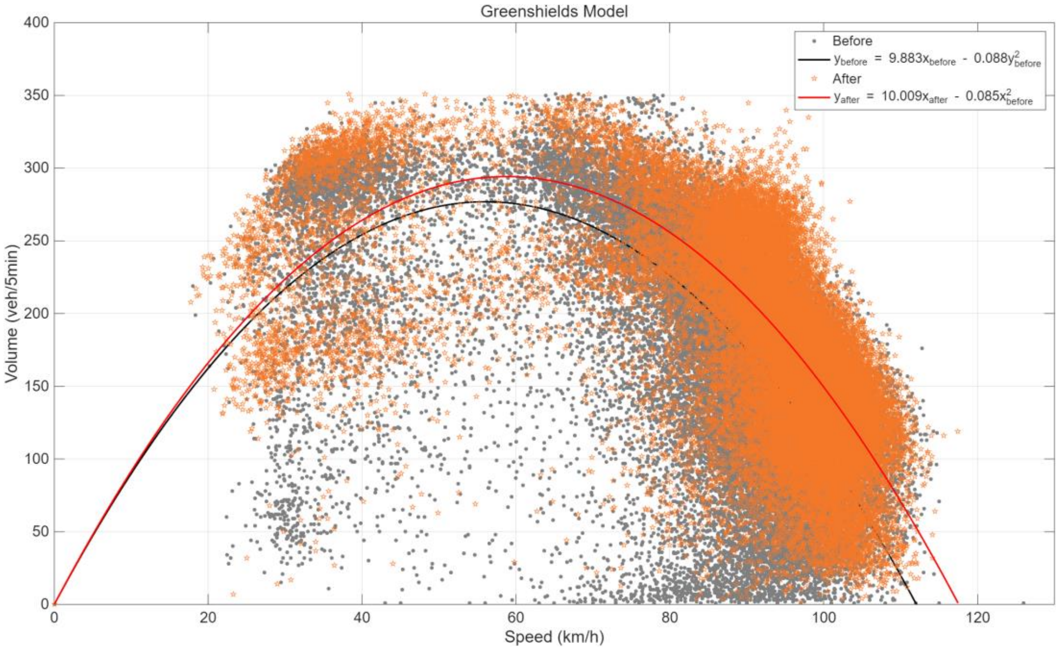


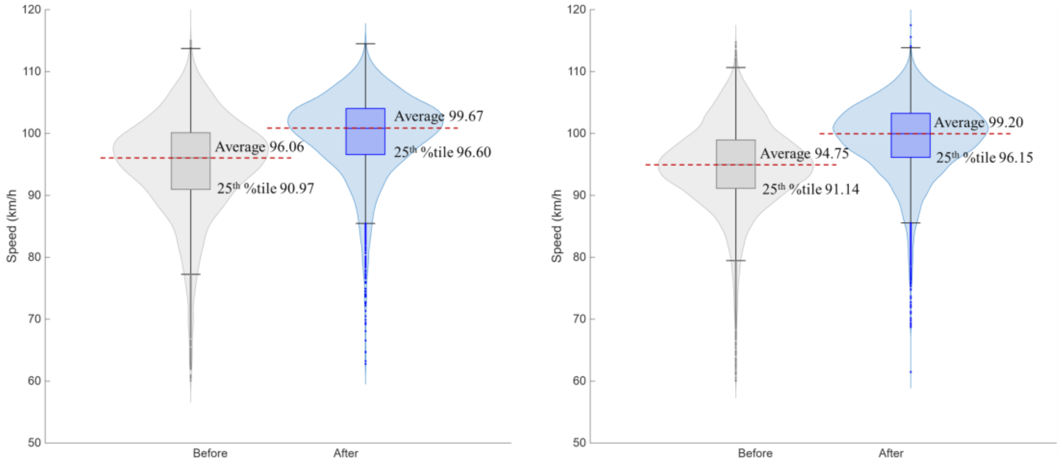
Figure 7. Speed–flow relationship before and after PMS implementation based on the Greenshields model.

4.3. Results of the Speed Improvement Analysis

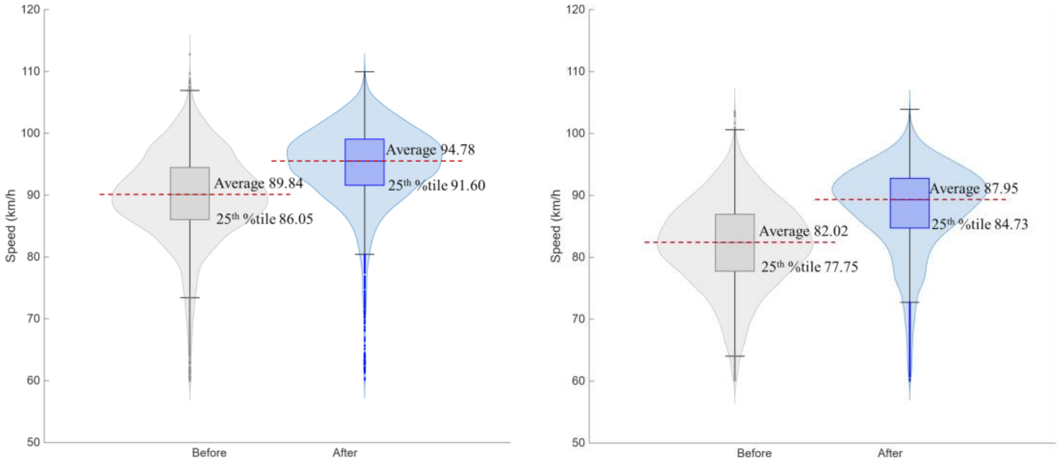
The descriptive statistics of speed before and after PMS implementation were compared for LOS A–F conditions and the results obtained are presented in Table 5. The speed distribution characteristics for each LOS condition before and after PMS implementation are shown in Figure 8.

Table 5. Descriptive statistics of speed for each LOS condition before and after PMS implementation.

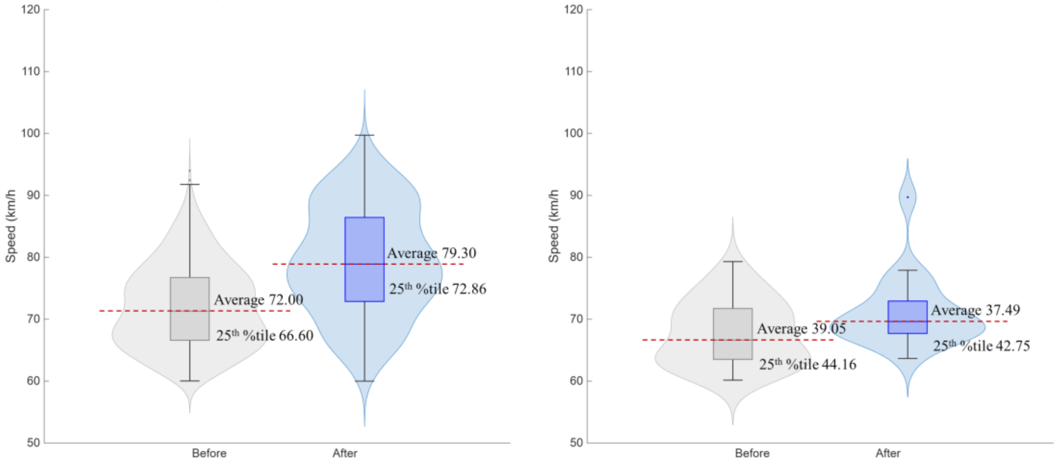
Speed (km/h)	**LOS A**		**LOS B**		**LOS C**		**LOS D**		**LOS E**		**LOS F**	
	Before	**After**	**Before**	**After**	**Before**	**After**	**Before**	**After**	**Before**	**After**	**Before**	**After**
Average	95.00	99.67	94.75	99.20	89.84	94.78	82.02	87.95	72.00	79.30	39.05	37.49
Median	96.06	100.84	94.96	99.96	90.10	95.50	82.38	89.30	71.32	78.90	37.35	36.56
Std.	8.00	6.68	6.83	5.97	7.07	6.36	7.03	6.95	6.76	8.85	9.28	9.15
Variance	63.94	44.67	46.67	35.70	49.94	40.40	49.42	48.31	45.74	78.30	86.17	83.69
Minimum	60.12	62.77	60.01	61.49	60.00	60.15	60.09	60.05	60.03	60.00	0.00	0.00
Maximum	126.00	114.50	114.76	117.47	112.81	109.96	103.53	103.90	94.01	99.73	59.98	59.93
15th %tile	87.66	93.70	88.70	93.56	83.55	89.25	74.84	81.15	64.76	69.25	31.16	27.96
25th %tile	90.97	96.60	91.14	96.15	86.05	91.60	77.75	84.73	66.60	72.86	32.90	31.04
75th %tile	100.12	104.03	98.96	103.25	94.48	99.06	86.93	92.75	76.75	86.45	44.16	42.75
85th %tile	102.42	105.69	101.55	104.86	97.10	100.78	89.23	94.33	79.42	89.74	49.50	47.13



(a) LOS A **(b)** LOS B



(c) LOS C **(d)** LOS D



(e) LOS E **(f)** LOS F

Figure 8. Comparison of the speed distributions of the vehicles for different LOS conditions before and after PMS implementation.

The average speeds generally increased after PMS implementation under LOS A–E conditions. Greater improvements were observed under LOS C–E conditions compared to others. In particular, the mean speed under LOS A increased from 95.00 to 99.67 km/h, corresponding to an increase of approximately 4.9%, whereas that under LOS B increased from 94.75 to 99.20 km/h, corresponding to an increase of 4.7%. Under LOS C and LOS D, the mean speed increased from 89.84 to 94.78 km/h and from 82.02 to 87.95 km/h, representing an increase of 5.5 and 7.2%, respectively. Under LOS E, the mean speed increased from 72.00 to 79.30 km/h, corresponding to an increase of approximately 10.1%. In contrast, under LOS F, the mean speed decreased slightly from 39.05 to 37.49 km/h, suggesting that the effect of PMS was limited under oversaturated conditions.

The 25th-percentile speed also increased under all LOS A–E conditions after PMS implementation. Under LOS A, the 25th-percentile speed increased from 90.97 to 96.60 km/h, corresponding to an increase of approximately 5.6%. Under LOS B, it increased from 91.14 to 96.15 km/h, corresponding to an increase of 5.5%. Under LOS C and LOS D, the values increased from 86.05 to 91.60 km/h and from 77.75 to 84.73 km/h, respectively, corresponding to an increase of 6.5 and 9.0%, respectively. Under LOS E, the 25th-percentile speed increased from 66.60 to 72.86 km/h, corresponding to an increase of approximately 9.4%. In contrast, under LOS F, the 25th-percentile speed decreased slightly from 32.90 to 31.04 km/h. These results indicate that the PMS was effective in alleviating the speed reduction among low-speed vehicles under LOS A–E conditions.

Further examination of the speed distribution characteristics showed that both the standard deviation and variance generally decreased after PMS implementation under LOS A–D conditions. This indicates that the PMS contributed not only to increasing the mean speed but also to reducing the speed variability among vehicles. Under LOS E condition, however, in addition to the increase in the mean and 25th-percentile speeds, the standard deviation and variance also increased slightly. This may be attributed to a temporary widening of the speed distribution caused by substantial speed recovery in a subset of vehicles under congested conditions.

To examine the statistical significance of the changes in the vehicle speed, both a normality test and a group difference test were performed. As shown in Table 6, the Kolmogorov–Smirnov test indicated that the speed data under LOS A–E conditions did not satisfy the normality assumption ($p < 0.05$). Therefore, the Mann–Whitney U test was applied. As presented in Table 7, the changes in the speed before and after PMS implementation were statistically significant under all LOS A–E conditions ($p < 0.05$). This indicates that the PMS provided significant speed improvement not only under free-flow conditions but also under stable and congested traffic conditions.

Table 6. Kolmogorov-Smirnov test results for the average vehicle speed under different LOS conditions.

Classification		Average speed		
		Statistic	df	Sig.
LOS A	Before	0.072	7546	0.000
	After	0.091	3538	0.000
LOS B	Before	0.050	13291	0.000
	After	0.064	9350	0.000
LOS C	Before	0.048	8755	0.000
	After	0.064	7161	0.000
LOS D	Before	0.029	6973	0.000
	After	0.092	6494	0.000
LOS E	Before	0.065	1920	0.000
	After	0.051	1531	0.000

Table 7. Mann-Whitney U test results for the average vehicle speed under different LOS conditions.

Average speed	LOS A	LOS B	LOS C	LOS D	LOS E
Mann-Whitney U	8,213,457	36,458,085	17,622,231	11,517,701	776,042
Wilcoxon W	36,688,288	124,790,071	55,951,621	35,832,552	2,620,202
Z	−32.701	−53.027	−47.595	−49.342	−23.856
Asymp. Sig. (2-tailed)	0.000	0.000	0.000	0.000	0.000

5. Conclusion

This study evaluated the effect of a PMS installed in the Geumnam Tunnel on the traffic flow through it using a before–after analysis based on long-term VDS data. The analysis was conducted from three perspectives: changes in the spatiotemporal traffic flow and traffic capacity, and improvement in the vehicle speed under different LOS conditions. The results provide empirical evidence that the PMS can improve the traffic flow by increasing the vehicle speed, reducing speed variability, and enhancing traffic flow stability.

The spatiotemporal traffic flow analysis showed that the average and 25th-percentile speeds increased at most VDS locations after PMS implementation, whereas the standard deviation of speed generally decreased. These changes were observed not only near the tunnel exit but also in the downstream sections, indicating that the effect of the PMS was not confined to the interior of the tunnel. In particular, the contour maps showed that the high-speed regions expanded and highly variable traffic conditions were reduced after PMS implementation. These results suggest that the PMS contributed to traffic flow recovery and speed harmonization in and around the tunnel section. The traffic capacity analysis based on the Greenshields model showed that the maximum traffic volume increased after PMS implementation. The estimated maximum traffic volume increased from 1661 veh/h/lane before to 1765 veh/h/lane after PMS implementation, which corresponds to a 6.3%

increase in traffic capacity. The fitted speed–flow curve after PMS implementation was located above that before PMS implementation and the vertex of the curve shifted upward. This indicates that the PMS improved the traffic processing capability of the tunnel section by mitigating phantom congestion and maintaining stable flow under higher traffic demand. The speed improvement analysis by LOS showed that the PMS was effective under LOS A–E conditions. The mean speed increased by approximately 6.5% on average, and the improvement was more pronounced under LOS C–E conditions. The 25th-percentile speed also increased under LOS A–E, indicating that the PMS alleviated speed reduction among low-speed vehicles. In contrast, the effect was limited under LOS F, where traffic demand exceeded the traffic capacity. Statistical tests further confirmed that the speed differences before and after PMS implementation were significant under all LOS A–E conditions. These findings indicate that the PMS was particularly effective under stable and moderately congested traffic conditions rather than under oversaturated conditions.

Overall, the results indicate that a PMS can improve the flow of traffic in tunnels by increasing the speed level, reducing speed variation, and enhancing traffic capacity. In practical terms, the PMS can be regarded as an effective operational measure for mitigating phantom congestion in tunnel sections. The findings of this study are expected to support future PMS deployment and contribute to the development of more efficient traffic management strategies in tunnels. Despite these promising results, several limitations remain. First, this study focused on a single tunnel section, and therefore the transferability of the findings of this study to other tunnel environments should be examined with caution. Second, although long-term VDS data were used, the effects of external factors such as weather conditions, accidents, and seasonal effects on the data, and thus the analysis, could not be fully controlled. Third, the analysis was conducted using aggregated detector data, which limits the direct interpretation of individual vehicle behavior and detailed car-following mechanisms. Future research should address these limitations. Comparative analyses across multiple tunnel sections are needed to verify the generalizability of the effect of a PMS. In addition, it is necessary to incorporate additional external variables, such as weather and accident information, to improve the reliability of the evaluation. In addition, future studies should investigate whether the effect of a PMS can be optimized through different operational settings, such as LED spacing, activation timing, and control strategies. Finally, it would be meaningful to combine detector-based analysis with trajectory-based or simulation-based approaches to efficiently explain the behavioral mechanism through which PMS improves the stability of traffic flow.

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Abbreviations

The following abbreviations are used in this manuscript:

PMS	Pacemaker system
VDS	Vehicle detection system
LOS	Levels of service

FHWA HSIP	Federal Highway Administration Highway Safety Improvement Program
%tile	Percentile

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