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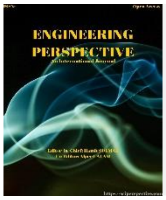

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Research Paper

Capacity Analysis Based on Vehicle Trajectory Data on a Weaving Bottleneck in Nanjing

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ABSTRACT

This paper investigates the capacity of weaving bottlenecks in Nanjing, where multiple traffic streams merge or diverge closely, causing significant traffic disruptions. Utilizing trajectory data from 862 vehicles collected through UAV cameras, the study assesses the bottleneck's capacity and performance measures, including traffic flow, speed, and lane occupancy. The analysis employs a combination of the Highway Capacity Manual (HCM) 2010 guidelines and PTV Vissim simulation software. The HCM 2010 framework provides a standardized approach for evaluating traffic flow characteristics and determining the level of service, while Vissim allows for the evaluation of diverse traffic scenarios.

The results reveal that the bottleneck operates at Level of Service E (LOS E), characterized by high congestion, reduced speeds, and prolonged travel times. However, introducing ramp metering to the area improves conditions, resulting in a transition to Level of Service D (LOS D). This study emphasizes the potential of ramp metering to enhance bottleneck performance. Nevertheless, future research should explore other strategies, such as intelligent transportation systems and improved public transportation services, to encourage modal shifts and reduce private vehicle usage. By addressing these challenges, cities like Nanjing can mitigate traffic congestion and create more efficient and sustainable transportation systems. The findings provide valuable insights for urban planners and policymakers seeking evidence-based solutions to optimize traffic flow and mobility in busy cities. By adopting the HCM 2010 guidelines and simulation tools like Vissim, this study contributes to the development of efficient traffic management strategies, ultimately fostering more livable and accessible urban environments.

Keywords: Traffic congestion; bottleneck capacity; weaving bottleneck; HCM 2010; PTV Vissim; LOS; Ramp metering

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1. Introduction

Urban areas worldwide are grappling with the persistent challenge of traffic congestion, which has far-reaching implications for travel efficiency, environmental sustainability, and quality of life. Effective management of congested bottlenecks is crucial to mitigate the negative impacts of congestion and optimize the performance of transportation networks. The capacity analysis of bottleneck sections plays a vital role in understanding traffic flow dynamics and identifying appropriate strategies for congestion reduction(Skabardonis et al., 2016). Numerous studies have focused on analyzing bottleneck capacity and proposing mitigation strategies using various methodologies. The Highway Capacity Manual (HCM) 2010, developed by the Transportation Research Board (TRB), serves as a fundamental reference for evaluating the operational performance and level of service (LOS) of transportation facilities.(Mahdi et al., 2022) The HCM 2010 guidelines provide standardized frameworks for assessing key parameters such as travel time, speed, lane changes, and flow rates to determine bottleneck capacity and LOS(Ryus, Vandehey, Elefteriadou, Dowling, et al., 2011).In parallel, the utilization of advanced simulation tools has revolutionized capacity analysis by allowing researchers to create virtual models of road networks and assess traffic flow under diverse scenarios(Raju et al., 2018). PTV Vissim, a widely adopted microscopic traffic simulation software, offers a powerful platform for analyzing traffic dynamics, simulating different traffic conditions, and evaluating performance measures within bottleneck sections(Suthanaya & Upadiana, 2019; WSDOT, 2014). This study aims to conduct a comprehensive capacity analysis of a weaving bottleneck in Nanjing, employing a combined methodology that incorporates the HCM 2010 guidelines and PTV Vissim simulation software. The primary objectives are to characterize traffic flow patterns, assess the bottleneck's LOS, and propose effective congestion reduction strategies to enhance traffic management.

The remainder of this paper is structured as follows: Section 2 presents materials and methodology, Section 3 provides results and discussion, outlining the application of the HCM 2010 guidelines and the use of PTV Vissim for simulation and presents the results of the capacity analysis, discussing the findings specific to the weaving bottleneck in Nanjing. Finally, Section 4 offers concluding remarks and suggestions for future research and implementation. Research on bottleneck capacity analysis has witnessed significant advancements in recent years. Many studies have utilized the HCM 2010 guidelines as a foundation for assessing and understanding the operational performance and LOS of bottlenecks.(Rouphail & Williams, n.d.) These studies have successfully applied the HCM 2010 methodologies to evaluate key parameters such as flow rates, speed, and lane changes, enabling a standardized assessment of bottleneck capacity. However, while the HCM 2010 provides a robust framework, some limitations exist in terms of its applicability to specific types of bottlenecks and the representation of certain traffic conditions(Raju et al., 2018). Moreover, the use of simulation tools, such as PTV Vissim, Anylogic, Ainsum, and Sumo, has significantly contributed to the analysis of bottleneck capacity and the exploration of congestion reduction strategies(Wang et al., 2014). Simulation-based studies have enabled researchers to create virtual models of road networks, evaluate various traffic scenarios, and estimate performance measures with a high degree of accuracy. These studies have highlighted the advantages of simulation-based approaches, including the ability to capture real-world complexities, investigate dynamic traffic patterns, and assess the impact of different operational strategies. However, it is important to consider the inherent limitations of simulations, such as the accuracy of input data and calibration of model parameters, to ensure reliable results(*Bottleneck-Removal-1-Pg*, n.d.). Despite the progress made in bottleneck capacity analysis, there are still knowledge gaps that warrant further investigation. For example, there is a need for more research on the capacity analysis of specific types of bottlenecks, such as complex urban intersections. Additionally, the interaction between bottleneck capacity and emerging technologies, such as connected and autonomous vehicles, requires further exploration to understand their influence on traffic flow and capacity(Zhao et al., 2017).

The existing research in bottleneck capacity analysis and congestion mitigation strategies has provided valuable insights and methodologies. However, there remains a need for current and future research projects to address several challenges. These include the development of more accurate and comprehensive models, the incorporation of real-time data for dynamic capacity analysis, the integration of intelligent transportation systems for improved traffic management, and the evaluation of sustainable transportation solutions to reduce congestion and environmental impacts. In light of the outlined research trends, strengths, weaknesses, knowledge gaps, and the need for further research, this study aims to contribute to the existing body of knowledge by conducting a capacity analysis of this bottleneck in Nanjing, employing a combined methodology of the HCM 2010 guidelines and PTV Vissim simulation software. The findings from this study will shed light on the specific characteristics of the weaving bottleneck and provide insights for effective congestion reduction strategies and improved traffic management in similar contexts.

2. Data collection

Secondary data was collected online from the website seutraffic.com, where it was recorded using an Av high-resolution camera. The data was captured within a duration of 450 seconds, encompassing trajectory data for 862 vehicles traveling unidirectional on a 5-lane highway, with the study area extending over a length of 386 meters.

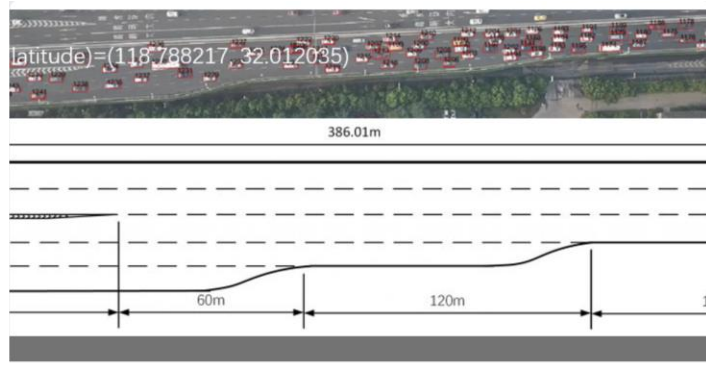

Figure 1. Bottleneck section under study (http://seutraffic.com/)

In this traffic configuration, there are three continuous lanes and two merging ramps that eventually converge into a downstream segment with three lanes as shown above in Figure 1. The collected dataset encompasses various attributes for each vehicle, including acceleration, vehicle ID, velocity, latitude, longitude, vehicle length, vehicle width, and lane ID, all observed at different time intervals. Accompanying this dataset is a video recording capturing the progression of each vehicle, from its entry into the bottleneck area to its exit. The analysis of this data reveals a significant frequency of lane changes within the merging section. Many drivers opt to reduce their speed or decelerate upon approaching the merging influence zone. Once they navigate past the merging zone, they resume acceleration and regain the free flow speed of 110 km/h. Notably, during the merging area, the free flow speed is determined to be 45 km/h, a finding drawn from the comprehensive data collection. Graphical representation of collected vehicle speeds is seen on Figure 2.

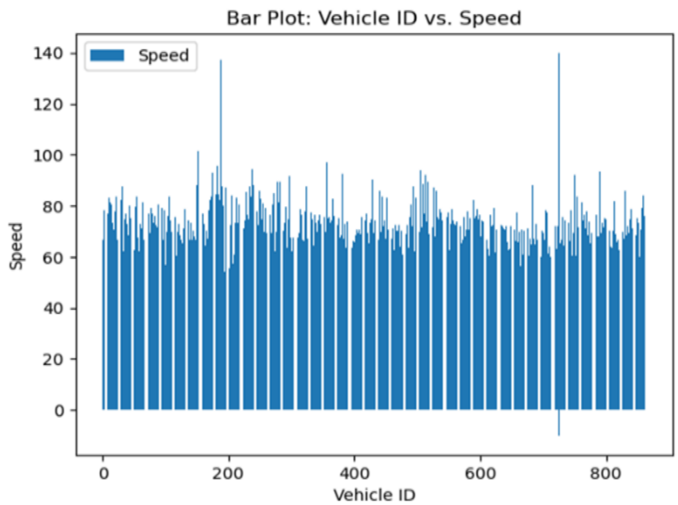

Figure 2. Vehicle ID vs Speed

3. Materials and Methodology

This study employed a mixed-methods approach to conduct a comprehensive capacity analysis of bottlenecks. The methodology consisted of two main components: the application of the Highway Capacity Manual (HCM) 2010 guidelines for capacity analysis and the utilization of PTV Vissim simulation software for traffic simulation. To assess the capacity of the weaving bottleneck, the HCM 2010 guidelines were utilized as a standardized framework. The guidelines provided a systematic approach for evaluating key parameters such as flow rates, speed, and lane changes. Data collection for the capacity analysis involved the extraction of recorded vehicle trajectory data at the bottleneck location. The collected data included vehicle speed, vehicle width, vehicle length, headways, lane positions, lane changes, and others. Using the HCM 2010 methodology, the extracted trajectory data were analyzed to calculate various performance measures such as the level of service (LOS), speeds, and flow rates. These measures provided insights into the operational performance of the bottleneck and facilitated the characterization of traffic flow patterns and congestion levels. Additionally, the HCM 2010 guidelines allowed for the identification of potential capacity constraints and bottlenecks within the weaving section. In parallel to the capacity analysis, traffic simulation using PTV Vissim software was conducted to further investigate the traffic dynamics and assess the performance of different congestion reduction strategies. PTV Vissim provided a powerful platform for creating a virtual model of the road network and simulating various traffic scenarios. The simulation model was calibrated and validated using the collected trajectory data to ensure its accuracy in representing real-world traffic conditions.

Once the simulation model was established, different operational strategies were evaluated to identify effective congestion reduction measures. These strategies included ramp metering and others. Through the simulation experiments, the impacts of each strategy on traffic flow, capacity, and LOS were assessed, enabling the identification of the most promising approaches for congestion mitigation. The capacity analysis results obtained from the HCM 2010 guidelines and the findings from the PTV Vissim simulations were integrated to provide a comprehensive understanding of the weaving bottleneck in Nanjing. The combined methodology allowed for a multi-dimensional analysis of the bottleneck, considering both the observed real-world data and the simulated scenarios. This integrated approach provided valuable insights into the traffic flow dynamics, capacity constraints, and potential congestion reduction strategies for the weaving bottleneck in Nanjing.

4. Results and discussion

4.1. Using HCM (2010)

The Highway Capacity Manual (HCM) 2010 is a widely used resource for analyzing and evaluating the operational performance of highways and transportation systems(Ryus, Vandehey, Elefteriadou, Dowling G, et al., 2011). It provides guidelines and methodologies for conducting various types of transportation analysis, including data analysis. The data collected were analyzed by doing calculations based on the guidelines of HCM (2010) where different flowrates, speeds, and other parameters have been calculated as detailed below:

Calculation of f_{HV} = heavy vehicle adjustment factor;

$$f_{HV} = \frac{1}{(1)+P_T(E_T-1)+P_R(E_R-1)} \quad (1)$$

where:
E_T and E_R are passenger car equivalents for trucks buses and recreational vehicles (RVS), respectively
P_T is the Proportion of trucks and buses, and RVS, respectively in the traffic stream
The terrain is in a class of level terrain hence, E_T (Truck and buses) is 1.5, and E_R for (RV_S) is 1.2. The proportion of Trucks and buses in collected data is 0.006 and 0.0015 respectively.

Then $f_{HV} = \frac{1}{(1)+0.006(1.5-1)+0.0015(1.2-1)} = 0.99$

Based on existing data, we have 6965 Veh/hr. where the free-flow speed in the downstream segment is 110 km/h and the free-flow speed at the merging influence area is 45km/h.

Conversion of volume (Veh/h) to flowrate pc/h;

Using this equation: $$v = \frac{V}{(PHF)(f_{HV})(f_p)} \quad (2)$$

Where V: is the hourly volume (veh/h), V is Peak 15-min flow rate in an hour (pc/h), f_{HV}: Heavy vehicle adjustment factor, f_p is: Driver population factor.

Peak Hour Factor (PHF) = $\frac{Hourly\ Volume}{\text{Peak flow rate (within hour)}} = 1$

Checking for maximum flow entering merge influence area;

$V_F = \frac{4776}{(1)(0.99)(1)} = 4824$ pc/h, $V_R = \frac{2120}{(1)(0.99)(1)} = 2141$ pc/h,

$V_{23} = V_{12}x1.12 = 4863 \text{ x } 1.12=3330$ pc/h

$\boldsymbol{V_{12}} = \frac{2944}{(1)(0.99)(1)}$=2974pc/h, ,

$\boldsymbol{V_{R23}}$ = V_{23}+V_R=3330+2141=5471pc/h and

$\boldsymbol{V_{FO}} = V_R + V_F$=4824+2141= 6965 pc/h,

Where: V_{12}: Flowrate entering ramp influence area (pc/h)
V_{R12} = sum of flow rates for ramp (V_R) and vehicles entering ramp influence area (pc/h);
$\boldsymbol{V_R}$ = flow rate on-ramp (pc/h)

For this analysis, we have two conditions;
Checking for 1st condition:
1st condition states that the total departing freeway flow (v) may exceed the capacity of the downstream freeway segment. Failure (LOS F) is expected. Here no further calculations are needed, and queues will form upstream from the merged segment. When the downstream freeway capacity is exceeded, LOS F exists regardless of whether the flow rate entering the ramp influence area exceeds its capacity. For the given road section, the free flow speed is 110 km/h at the downstream street with 3 lanes in the same direction. Hence the estimated capacity (V_{FO}) of the downstream segment is 6965 pc/h which is less than 7050 pc/h which is suggested by HCM LOS F will not exist.

Table 1. Capacity values for merge area (*Highway Capacity Manual 2000 RAMPS AND RAMP JUNCTIONS CONTENTS*, n.d.)

Freeway Free-Flow Speed(km/h)	Maximum Downstream Freeway Flow, v(pc/h)				V_{R12} (pc/h/ln)
	Number of Lanes in One Direction				
	2	3	4	>4	
120	4800	7200	9600	2400	4600
110	4700	7050	9400	2350	4600
100	4600	6900	9200	2300	4600
90	4500	6750	9000	2250	4600

V_{R12} is the Maximum Downstream Freeway Flow**.** Checking for maximum flow entering merge influence area;
For our case, we have V_{R12}=V_{12}+V_R=2697+2141=4838pc/h, here based on Table 1 (Exhibit 25-7 in HCM 2010)The maximum flow entering the influence area exceeds the desired maximum flow as recommended by HCM, but there will be no LOS F according to this second condition:

2nd condition states that when the total flow entering the ramp influence area exceeds its maximum desirable level but the total freeway flow (v) does not exceed the capacity of the downstream freeway segment. In this case, locally high densities are expected, but no queuing is expected on the freeway. The actual lane distribution of entering vehicles is likely to consist of more vehicles in the outer lanes than is indicated by the models herein. Overall, the operation will remain stable, and LOS F is not expected to occur. But when the total downstream flow exceeds the basic freeway capacity of the downstream segment, LOS F exists. In such cases, no further computations are needed, and LOS F is assigned. For all other cases, including cases in which VR_{12} exceeds its stated limit, LOS is determined by estimating the density in the ramp influence area.

4.1.1. Calculating level of service (LOS)

Computing density;

This equation is used to estimate the density in the merge influence area

$$D_R = 3.402 + 0.00456V_R + 0.0048V_{12} - 0.01278L_A \qquad (3)$$

$L_{Aeff} = 2L_{A1} + L_{A2}$

where: D_R: Density of merge influence area (pc/km/ln), V_R: On-ramp peak 15-min flowrate (pc/h), V_{12}: Flowrate entering ramp influence area (pc/h), L_A: Length of acceleration lane (m)

D_R=3.402+0.00456*2141+0.0048*2974-0.01278*240

=24.37pc/km/ln. Basing on exhibit 25-7 in HCM(2000) and also as it shown in table 2, we were able to determine the Level of Service of the section under study.

Table 2. LOS criteria for merging and diverging (Ryus, Vandehey, Elefteriadou, Dowling, et al., 2011)

LOS	Density (pc/km/ln)
A	≤6
B	>6-12
C	>12-17
D	>17-22
E	>22
F	Demand exceeds capacity

The merging area is under LOS E as the density of the merging influence area is greater than 22pc/km/ln (see Table 2).

4.1.2. Characteristics of LOS E;

LOS E is indicative of moderately congested traffic flow. It implies that the roadway is operating at or near its capacity, and vehicles are traveling at speeds slightly below the posted speed limit. Vehicles in LOS E experience reduced speeds compared to free-flow conditions, with the average speed typically around 45-50% of the posted speed limit. Traffic density in LOS E is relatively high, and vehicles are closely spaced. The roadway is operating at or near its maximum capacity. Travel time in LOS E is longer than under free-flow conditions, with moderate delays and periodic fluctuations in speed due to congestion. Vehicles in LOS E may frequently need to accelerate and decelerate due to the changing traffic conditions. This is particularly evident in areas with merging lanes, intersections, or other areas where traffic flow is disrupted(*Highway Capacity and Level of Service*, 1991; Volosenko & Laurinavičius, 2020).
Although lane changes may still occur in LOS E, they may be less frequent and more difficult due to the high traffic volume and limited gaps between vehicles. The roadway is operating at or near its maximum capacity, and small disruptions or fluctuations in traffic flow can quickly lead to congestion or breakdown conditions. LOS E may be perceived as moderately uncomfortable for

drivers. The close proximity of vehicles and the need for frequent adjustments in speed and position can contribute to a higher level of driver stress. Safety concerns may arise in LOS E due to the increased traffic density and closer spacing of vehicles, with a slightly higher risk of rear-end collisions, lane merging conflicts, and other traffic-related incidents compared to lower levels of service (Abdullah & Sadullah, 2017)

4.1.3. Computing speeds as supplemental information;

Finding average speed in the outer lane Ramp influences area;

$$M_S = 0.321 + 0.0039e^{\frac{V_{R12}}{1000}} - 0.004(\text{LAeff}S_{FR}/1000)$$

S_{FR} is the free-flow speed of the ramp (km/h);

$L_{Aeff} = 2LA1 + LA2$=240m

where: L_{Aeff} Is the effective length of the acceleration lane

$S_{FR} = 45km/h,$ Here it indicates that the capacity of the ramp roadway itself should be 3500 pc/h for Two-Lane Ramps according to Exhibit 25-3 in HCM2010

M_S =0.321+0.492-0.0432=0.77 where: M_s is the intermediate speed determination variable for the merge area

$$S_R = S_{FF} - (S_{FF} - 67)M_S$$

S_R =110-(110-67) *0.77=76.89 Km/h

$$V_{OA} = \frac{V_F - V_{12}}{N_O} = \frac{4824-2974}{2} = 925\text{pc/h}$$

Where V_{OA} = average per-lane flow rate in outer lanes at begin of ramp influence area

SR = space mean speed of vehicles within ramp influence area (km/h); for merge areas, this includes all vehicles in VR_{12}; for diverge areas, this includes all vehicles in V_{12}

Here V_{OA} lies between 500pc/h to 2300 pc/h, then the second formula in HCM has been used;

$S_O = S_{FF} - 0.0058(V_{OA} - 500)$, S_O= 110−0.0058(925-500) =107.535Km/h

$$\boldsymbol{S_w} = \frac{V_{12} + V_{OA}N_O}{\frac{V_{12}}{S_R} + \frac{V_{OA}N_O}{S_O}} = 86.31\text{Km/h}$$

where: S_O = space mean speed of vehicles traveling in outer lanes (Lanes 3 and 4, where they exist) within 450-m length range of ramp influence area (km/h);

SFF = free-flow speed of freeway approaching merge or diverge area (km/h);

VR12 = sum of flow rates for ramp (VR) and vehicles entering ramp influence area (pc/h);

VOA = average per-lane flow rate in outer lanes at the beginning of ramp influence area

NO = number of outside lanes in one direction (not including acceleration or Deceleration lanes or Lanes 1 and 2),

VF = total approaching freeway flow rate (pc/h), and

V12 = demand flow rate approaching ramp influence area (pc/h)

4.2. Simulation of collected data using PTV VISSIM

PTV Vissim is a leading software application for microscopic traffic simulation. It is widely used by transportation professionals and researchers to model and analyze traffic operations and behavior in various transportation systems. PTV Vissim enables users to simulate and visualize the movement of individual vehicles and their interactions within a detailed virtual environment (Planung Transport Verkehr GmbH - Copyright, 2022; Utomo et al., 2020).

Setting Up the VISSIM Model for the Study Area;

VISISM needs to prepare to run the simulation of estimating the capacity of the study area. There are a few steps in VISISM microsimulation that have been described below.

1. An overlapped geometry of the study section was drawn in where the total section of the bottleneck was redrawn in VISSIM as it is shown in Figure 3.
2. Next, five types of vehicles were selected. Car and heavy goods vehicles (HGV) are considered traditional vehicles, For all types of vehicles, driving behavior was determined as Freeway (free lane selection)
3. The desired speed was customized as a requirement. In this paper, a total of 8 types of speed distributions were selected with lower and upper bounds. The calibration, validation, and simulation setup for various free-flow speeds describes a detailed speed distribution.
4. The next part includes vehicle composition, In the vehicle input part, traffic demand needs to be set as input. This demand value was found in the collected data. For capacity checking, traffic demand was kept at 6965veh/h for all five lanes. For vehicle inputs, each lane was given a number of vehicles that is similar to that one contained in collected trajectory data. The first 3 minutes were spent for warm-up, which means running different vehicles initially and counting for the next 60 minutes.
5. Finally, the simulation parameter setup and evaluation parameter setup were completed to get the result. A total of 3 data collection points were set up at the end of each lane to get the VISSIM output.

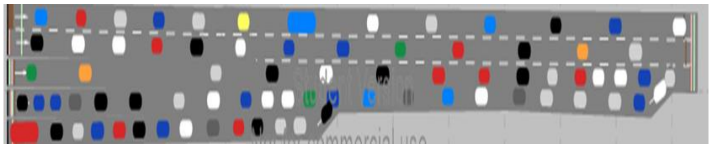

Figure 3. First simulation in Vissim without Ramp metering

4.3. Simulation Results

The results of this simulation were characterized by congested traffic conditions in the merging influence areas as it is shown in Figure 3 and in table 3, The simulation results proven it, as it is characterized by with long queues, slow speeds, and significant delays. The simulation results demonstrate a decrease in average and maximum speeds compared to other free-flow conditions, indicating reduced mobility and capacity utilization on the road network. The congestion leads to increased travel times, with longer journey durations, moreover, it was associated with reduced traffic flow rates. In order to propose a method by which the performance of this bottleneck can be improved, the simulation was repeated with the same conditions as the first one. But by applying ramp metering at the entrance ramps as it is shown in Figure 4, Ramp metering was applied to section of the road under study. Ramp metering systems typically consist of traffic signals installed at the entrance ramps. After setting ramp metering to VISSIM software the simulation was repeated again. After the ending of the second simulation, the results showed reduced queuing and improved overall performance of the bottleneck as its capacity falls under LOS D. And also, simulation results demonstrated a noticeable reduction in delays and smoother traffic progression through the bottleneck.

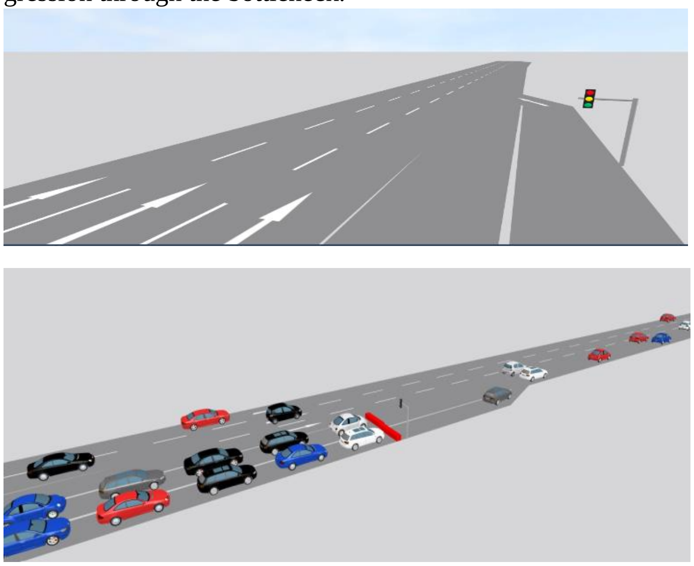

Figure 4. Second simulation process after application of Ramp metering

The effectiveness of these strategies was assessed through comprehensive performance metrics derived from the simulation results. Figure 4 also proves the successful contribution of Ramp metering to the reduction of Queue length, as there are some empty spaces between moving vehicles.

Table 3. VISSIM simulation results before and after the application of Ramp metering

Performance Indicator	**Before Ramp Metering**	**After Ramp Metering**
Average free flow Speed for downstream segment (km/h)	110	120
Average Merge area speed (km/h)	76.89	87.4
Queue Length (m)	102	40
Delay (s/vehicle)	85	32
Calculated Density (pc/km/ln)	24.37	20.2

The simulation demonstrated a significant improvement in the performance of the bottleneck, as evidenced by reduced queue lengths, improved average speeds, and decreased travel delays. These positive outcomes validate the efficacy of the implemented strategies and highlight the potential benefits of using PTV Vissim simulation as a decision-support tool for bottleneck management.Top of Form

5. Results interpretation

After conducting the analysis using the Highway Capacity Manual (HCM) methodology and simulating the performance of the bottleneck using VISSIM, the results indicated that the Level of Service (LOS) of the bottleneck was initially evaluated as E. This LOS suggests significant congestion and delays, indicating a suboptimal traffic flow. To improve the performance of the bottleneck, a ramp metering strategy was implemented using VISSIM simulation. The ramp metering approach involved controlling the flow of vehicles entering the mainline from the on-ramp. By regulating the rate at which vehicles merge onto the mainline, it aims to alleviate congestion and enhance overall traffic flow efficiency. The comparison of results before and after the implementation of ramp metering provides significant insights into the effectiveness of this traffic management strategy. The average free-flow speed for the downstream segment saw a notable increase from 110 km/h to 120 km/h after ramp metering was introduced. This improvement signifies enhanced traffic flow and better mobility within the downstream segment, attributed to the controlled entry of vehicles through ramp metering.

The merge area speed, a critical factor in bottleneck performance, exhibited a positive change as well. Prior to ramp metering, the merge area speed was 76.89 km/h, which notably rose to 87.4 km/h post-implementation. This change indicates that the introduction of ramp metering has facilitated smoother merging of vehicles at higher speeds, effectively reducing the potential for congestion and delays in this critical zone.

The queue length, often indicative of the level of congestion and delays experienced by drivers, showed a substantial reduction from 102 meters before ramp metering to a significantly diminished 40 meters after its application. This reduction in queue length translates to shorter waiting times for vehicles at the merge point, resulting in improved traffic flow and a less congested roadway environment.

One of the most critical aspects, delay per vehicle, experienced a substantial decrease from 85 seconds to 32 seconds following the implementation of ramp metering. This decrease indicates that vehicles spent significantly less time in traffic queues, leading to shorter travel times and an overall enhancement in traffic efficiency. Additionally, the density of vehicles on the roadway, a vital measure of traffic congestion, exhibited a positive change. Density decreased from 24.37 pc/km/ln to 20.2 pc/km/ln after ramp metering. This reduction implies that vehicles were better spaced out, contributing to smoother traffic flow and a less congested road network.

Overall, the Level of Service (LOS) transitioned from E to D after ramp metering was introduced. This shift underscores a substantial enhancement in the overall traffic conditions, with reduced congestion, lowered delays, and improved traffic flow. Top of Form

The successful implementation of ramp metering suggests its effectiveness in mitigating congestion and improving the bottleneck's performance. The results align with previous studies and empirical evidence supporting the positive impact of ramp metering on traffic flow and capacity enhancement. These findings demonstrate the practical application of the HCM methodology in evaluating bottlenecks and identifying potential solutions for improving traffic performance. Moreover, the VISSIM simulation provided a valuable platform to assess the effectiveness of the ramp metering strategy and its impact on the bottleneck's LOS.

6. Conclusions

In conclusion, the application of the Highway Capacity Manual (HCM) methodology combined with VISSIM simulation has provided valuable insights into the performance of a bottleneck and the effectiveness of a ramp metering strategy. The initial evaluation of the bottleneck indicated a Level of Service (LOS) E, highlighting significant congestion and delays. However, after implementing the ramp metering strategy in the simulation, the LOS improved to D, indicating a noticeable enhancement in traffic flow and a reduction in congestion. These results align with previous studies [2] that have demonstrated the effectiveness of ramp metering in improving traffic performance. The successful application of the HCM methodology and VISSIM simulation emphasizes the importance of utilizing advanced tools and techniques for traffic analysis and mitigation strategies. By employing these methods, transportation planners and engineers can gain valuable insights into the causes of congestion and identify effective solutions for enhancing traffic flow and reducing delays.

The results strongly suggest the implementation of a ramp metering strategy at the bottleneck location to improve traffic flow and reduce congestion. Ramp metering should be further studied and optimized by considering factors such as traffic demand patterns, control algorithms, and coordination with adjacent intersections.

Continuous Monitoring and Evaluation: Regular monitoring and evaluation of the bottleneck's performance are crucial to identify any changes in traffic conditions and assess the effectiveness of the implemented ramp metering strategy. This will enable transportation authorities to make timely adjustments and fine-tune the system for optimal performance.

Integration of ITS technologies, such as real-time traffic monitoring, adaptive control systems, and advanced data analytics, can further enhance the effectiveness of the ramp metering strategy. These technologies can provide valuable data for decision-making, optimize control parameters, and facilitate proactive traffic management. Comprehensive Analysis of Alternative Strategies: While ramp metering has shown promising results, it is essential to explore alternative strategies and conduct a comprehensive analysis to identify the most effective combination of measures for further improving the bottleneck's performance. This may include considering changes in lane configurations, signal timing adjustments, or other operational and infrastructure improvements. By implementing these recommendations, transportation agencies can strive towards achieving a more efficient and sustainable transportation system, providing better mobility and reducing congestion for the traveling public.

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Conflict of interest declaration:

The authors declare that they have no conflicts of interest concerning this article.

Credit Author Statement

Sugira Jean Claude: Conceptualization of the study, devising the methodology, developing the necessary software tools for data analysis, writing of the original draft.
Nshimiyimana Marc: Conceptualizing the research, overseeing the project's progress, and writing the original draft.
Nsengimana Jean Pierre: Curating the trajectory data collected from the website "seutraffic.com.", visual representations, and interpretation of the results.

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