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Monitoring of Urban Roadway Safety Hazards from Existing Bus-based Video Imagery: Phase 2

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16. Abstract

Contributors to traffic safety hazards include lane changes in the presence of queues at signalized intersections and bus stops, mixes of vehicle classes, speed variability, and vehicle overtaking. Traditional data collection methods that are constrained in time and space are prone to biased sampling. Taking advantage of video imagery recorded by transit bus-mounted cameras for other purposes offers an opportunity to overcome this bias. In this project the available, repeated, and extensive imagery recorded by such cameras for identifying queue presence and length related safety hazards is investigated. The increased presence of queues in association with construction zones is also explored. The campus of The Ohio State University roadway network is used as a living lab testbed. The results demonstrate the feasibility of the approach in identifying queuing over space, including around construction zones, and time. Further improvements and extensions are discussed.

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Safety21 University Transportation Center Report

Project 503: Monitoring of Urban Roadway Safety Hazards from Existing Bus-based Video Imagery: Phase 2

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Abstract

Contributors to traffic safety hazards include lane changes in the presence of queues at signalized intersections and bus stops, mixes of vehicle classes, speed variability, and vehicle overtaking. Traditional data collection methods that are constrained in time and space are prone to biased sampling. Taking advantage of video imagery recorded by transit bus-mounted cameras for other purposes offers an opportunity to overcome this bias. In this project the available, repeated, and extensive imagery recorded by such cameras for identifying queue presence and length related safety hazards is investigated. The increased presence of queues in association with construction zones is also explored. The campus of The Ohio State University roadway network is used as a living lab testbed. The results demonstrate the feasibility of the approach in identifying queuing over space, including around construction zones, and time. Further improvements and extensions are discussed.

1. Introduction and Motivation

Contributors to traffic safety hazards include lane changes in the presence of queues at signalized intersections and bus stops, mixes of vehicle classes, speed variability, and vehicle overtaking. Assessing locations with increased recurring traffic safety hazards requires extensive and ongoing collection of data on these contributors. Traditional methods entail using sensors at permanent or temporary fixed locations, which is costly and labor intensive and provides limited coverage over time and space. Moreover, the location of these sensors may be influenced by factors other than optimal sampling, such as requests from well-organized constituencies. Therefore, relying on such data to assess traffic safety hazards to support improved policies and designs could lead to missing high-risk conditions resulting in inequitable outcomes.

Clearly, low cost and extensive, equitable data collection is desirable. Transit buses operate regularly over wide networks. Most agencies have equipped their bus fleet with cameras that record the environment inside and outside buses for liability, security, and safety purposes. Consequently, the imagery is available for other uses at near-zero marginal cost, and the coverage provides comprehensive views that could potentially be used to determine times and locations of regularly occurring safety hazards. Moreover, this imagery has been shown by project investigators to be effective in monitoring traffic volumes across time and space, information that provides exposure-based context for identifying safety hazards. Furthermore, in a previous phase 1 project, an automatic queue presence and length identification method is developed and evaluated where promising results were arrived at. In this phase 2 project identifying hazardous queuing related “hotspots” over a roadway network by time-of-day using extensive imagery recorded by cameras mounted on transit buses in regular operation is investigated and demonstrated.

This project addresses the “Data-driven System Safety” research priority outlined in US DOT Research, Development and Technology Strategic Plan (RD&T Plan). Specifically, the long-term effort relates to the following: (1) “Safe Design” whereby assessing safety hazards that relate to cyclists, scooterists, and motorcyclists and determining the percentage of these vulnerable vehicles involves “Identify[ing] and support[ing] strategies to increase vulnerable road user safety” (see p. 19 of RD&T Plan). (2) “Safety Data” whereby the project focuses on “Develop[ing] safety data collection methods and advance[ing] safety data … to identify and analyze emerging safety issues” and “Improv[ing] safety data systems . . . to improve analy[zing] and identify[ing] emerging safety risks and disparate safety impacts on people and communities” (see p. 19 of RD&T Plan). (3) “Safe Technology” whereby the project involves “Leverag[ing] innovative (nonintrusive, i.e., safe) technologies to monitor, predict, and plan ways to reduce injuries and fatalities among the transportation workforce and traveling public” (see p. 19 of RD&T Plan).

The literature emphasizes the importance of traffic safety monitoring. Some studies address safety aspects related to the presence of pedestrians, cyclists, and motorcyclist in the traffic stream and safety aspects related to work zones (Howarth, 1982; Rouphail and Jovanis, 1987; Marlow, 1990; Jernigan and Lynn, 1995; Tsai, 2011; Mollenhauer et al., 2019; Still and Still, 2019). A few studies refer to the use of imagery for the purpose of monitoring (MacCarley, 1997; Rezaei, 2014; Yang et al., 2018). However, none of the studies address the importance of and ability to achieve time- and space-comprehensive queue presence data collection for the purpose of safety hazard monitoring and assessment, which is the focus of this study.

Two investigations are conducted in this study. One is related to the impact of construction zones on queue formation and therefore to construction zones presenting increased safety hazard risks. The other is related to the assessment of increased queue safety hazard risks across a network of roadways over time-of-day.

2. Methodology

2.1 Testbed and Extraction of Vehicle Data from Video Imagery

In a previous study (McCord et al., 2023; McCord et al., 2025), the investigators obtained transit bus-based video imagery to estimate traffic flows across The Ohio State University (OSU) campus and provide summary results to campus planners and operators on a regular basis. The video-based sensing set-up is shown in Figure 1. The OSU campus is again used in the present study as a living lab testbed for this study. The size and diversity of land uses make the campus representative of urban areas. Moreover, the campus has been undergoing major construction activities, which allow investigation of different infrastructure conditions that could influence traffic safety.

Video imagery files are downloaded from the Campus Area Bus Service (CABS) buses by the team’s outreach partner, OSU’s Transportation and Traffic Management (TTM). Depending on one of the two related investigations conducted in this study, data are extracted either manually or semi-automatically. For the impact of construction zones on queue formation investigation, queue information is extracted manually. For the assessment of space-time increased safety hazard risk (“hotspots”) investigation, a semi-automatic graphical user interface (GUI) is used by undergraduate and graduate research assistants to extract data on vehicles passing buses in the opposite direction of the buses’ travel direction (McCord et al., 2020).

The purpose of the use of the GUI is to demonstrate the potential of using video imagery recorded by bus-mounted cameras. For the approach to be cost-effective for ongoing and frequent monitoring of large networks in practice, it is desirable to automatically identify vehicles in the imagery. Automatic vehicle identification appears feasible given results from research to automatically identify vehicles from mobile video imagery using machine vision methods (Redmill et al., 2023). When operational automatic vehicle identification is achieved, the marginal cost of processing the video imagery to extract queuing information would become minimal, as is the present marginal cost of accessing the video imagery.

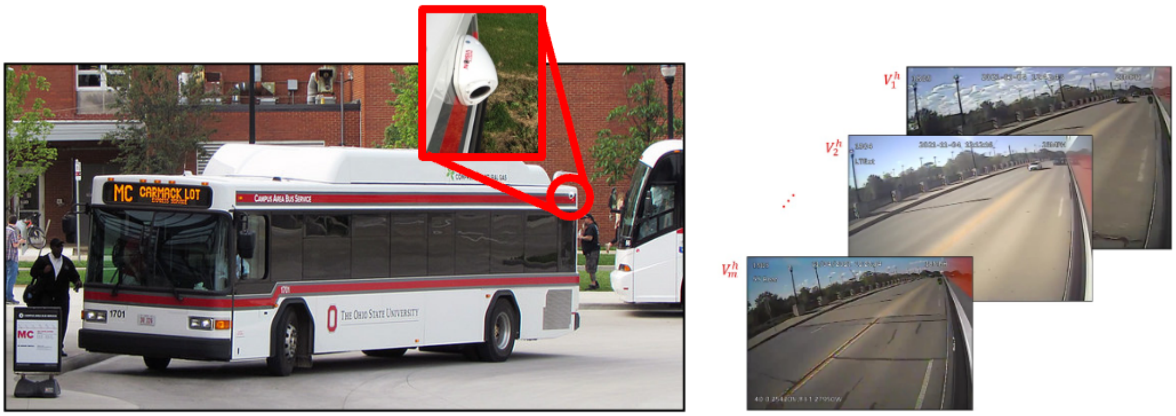


Figure 1: Bus-based video roadway monitoring set-up

2.2 Queue Identification

For the impact of construction investigation, queues are identified and their lengths, measured in number of vehicles, are counted manually. For the "hotspots" investigation, the automatic queue presence and length determination method developed in the year 1 project (Mishalani et al., 2024) is applied. The method considers the interarrival times between vehicle observations identified in bus-based imagery along roadway segments following the method described in section 2.1. The roadway location and timestamp output from the GUI are used to measure the vehicle interarrival times of interest. An interarrival time less than or equal to 2 seconds (which corresponds to 20 video frames recorded at 10 frames/sec) is used in this study to indicate that the corresponding two vehicles are part of a queue. The number of vehicles in the queue is then set equal to the number of consecutive interarrival times less than the threshold plus one. In addition, a minimum number of vehicles that satisfy the interarrival time threshold, V_{min}, must be seen to consider a queue to have occurred. In this study, two cases for V_{min} are considered, 2 and 4. The value of V_{min} = 2 is used for comparison purposes, since two vehicles recorded as being close together in time could represent vehicles close to each other in adjacent lanes when there is more than one lane of traffic being observed, or a moving pair of vehicles with temporarily small spacing. The value of V_{min} = 4 is considered more reasonable to reduce the likelihood of overidentification.

2.3 Queue Metrics for Safety Hazard Identification

Several queue related variables were considered for the purpose of assessing safety risk. The following variables are selected for use in this study:

- $PLNQV$ = total number of vehicles in all queues identified to have occurred on a segment-direction for a given bus pass, and
- $PLNDQ$ = number of different queues identified to have occurred on a segment-direction for a given bus pass.

The impact of construction investigation is conducted at the bus pass level and, therefore, observations of $PLNQV$ are used. The "hotspots" investigation is conducted at the hour-of-the-day level and, therefore, the values of the two bus pass level variables defined above are averaged for a given segment-direction-hour i and are denoted by NQV_i and NDQ_i for the average hourly number of vehicles in queues and the average number of different queues, respectively.

3 Data and Results

3.1 Data

The data used for each of the two investigations are discussed as follows.

3.1.1 Data for Construction Zone Impact on Safety Hazard Risk

In the spring, summer, and fall of 2024, roadway construction occurred along segment 4.1 (see discussion and map in section 3.1.2) spanning the Woody Hayes bridge of the OSU campus in the eastbound direction. From imagery of eastbound vehicles recorded by cameras mounted on CABS buses traversing the segment in the westbound direction on September 9,10,16,17, 23 and 24, 2024, an experienced graduate student manually identified the presence of queues and counted the total number of queued vehicles as seen in association with each of the bus passes. These data form the primary inputs for the investigation of the impact of the presence of construction on the total number of queued vehicles resulting in a safety hazard risk.

3.1.2 Data for Identifying Space-Time Safety Hazard Risk

Video imagery recorded on OSU's CABS buses transversing the campus network on October 31, 2024, from 7 am to 7 pm were downloaded by TTM, the project's outreach partner, and provided to the project's research team. The roadway segments comprising the campus network considered are shown in Figure 2. The segments are numbered in a manner that distinguishes their direction. The X.1 directions indicate eastbound or northbound traffic, and the X.2 directions indicate westbound or southbound traffic.

A total of 748 video clips spanning 64.7 hours of imagery are processed semi-automatically using the GUI discussed in section 2.1 by 13 undergraduate students and 4 graduate students for their term project in CIVILEN 5720 Transportation Engineering Data Collection Studies (see section 4) and 3 undergraduate research assistants hired to work on this research project.

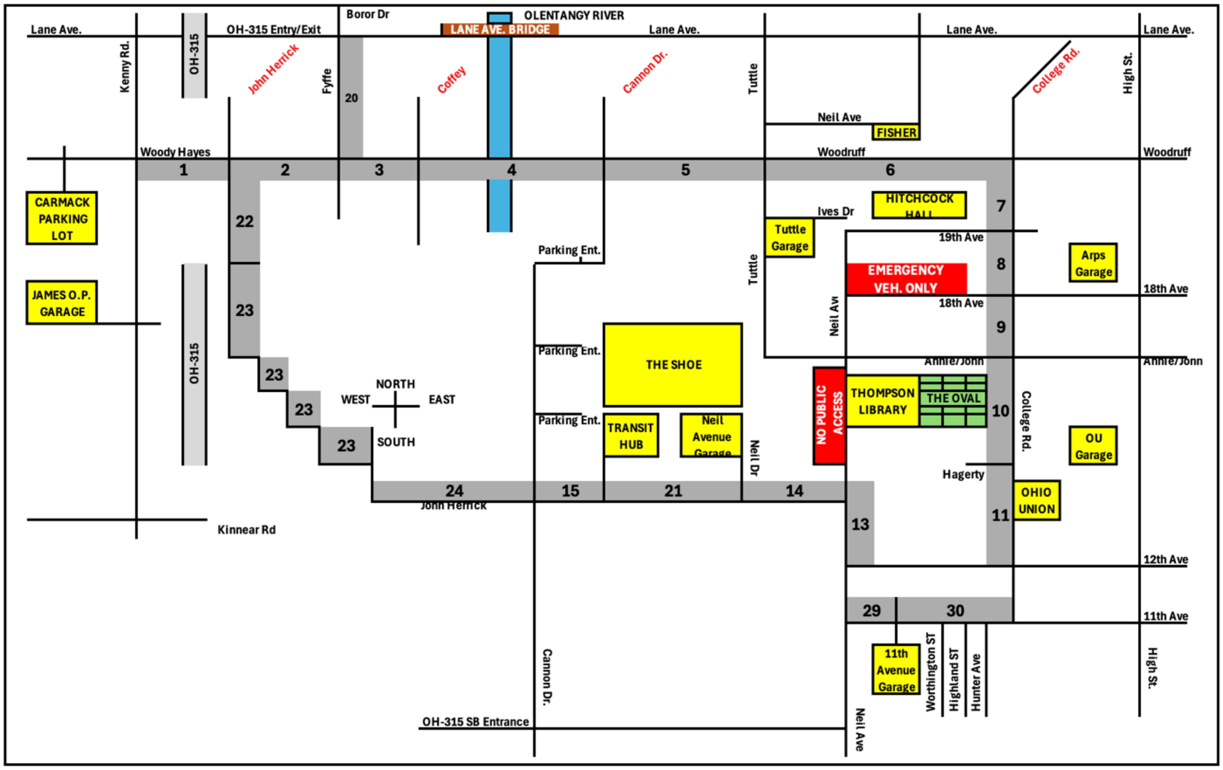


Figure 2: Illustration of OSU campus roadway network and segment numbers

3.2 Results

Similar to the presentation in section 3.1, results are presented for the impact of construction and "hotspots" investigations as follows.

3.2.1 Construction Zone Effect on Queuing and Safety Hazard

To investigate the impact of construction zones on queue formation and therefore the possible increased safety hazard risk associated with construction zones, the bus pass level total number of vehicles in queues on segment 4.1 observed in the video imagery over multiple bus passes, $PLNQV$, is investigated considering the status of construction leading to the partial closure of this roadway segment through the setup of a construction zone. More specifically, the construction led to the closure of the right lane of the two lanes of the eastbound roadway segment over the Woody Hayes bridge. Two locations along the bridge lend an opportunity for queues to form: one location upstream of the signalized intersection at the downstream end of the segment-direction and a second location mid-segment, upstream of a combined pedestrian crosswalk and an unsignalized, left-turn entrance to a parking lot. The construction zone spans a length along the segment-direction some short distance upstream of the downstream end and stretching upstream well past the walkway and unsignalized intersection.

The summary statistics of the variable $PLNQV$ for each of the two cases, in the absence and in the presence of construction, are shown in Table 1. Clearly, the sample mean and median values for the absence of construction case are less than the corresponding values for the presence of construction case. In addition, the non-parametric Wilcoxon test of the null hypothesis that the medians are equal is rejected at a p-value of 0.0407 and the parametric Welch t-test of the null hypothesis that the means are equal is rejected at a p-value of 0.00145. Furthermore, the empirical cumulative distribution functions (ECDFs) of $PLNQV$ for the two cases are shown in Figure 3. Most of the values of $PLNQV$ for the absence of construction case are appreciably less than the values for the presence of construction case. Moreover, the non-parametric Kolmogorov-Smirnov (KS) test of the null hypothesis that the CDFs are equal is rejected at a p-value of 0.0342.

Table 1: Summary statistics of $PLNQV$ in the absence and presence of construction

Statistic	Construction absent (lane open)	Construction present (lane closed)
Average Number of queued vehicles	11.45	26.78
Variance	51.07	406.48
Standard deviation	7.14	20.16
Median	8	21
No. of Observations (bus passes)	11	27
Dates of Observations in September 2024	23, 24	9,10,16,17

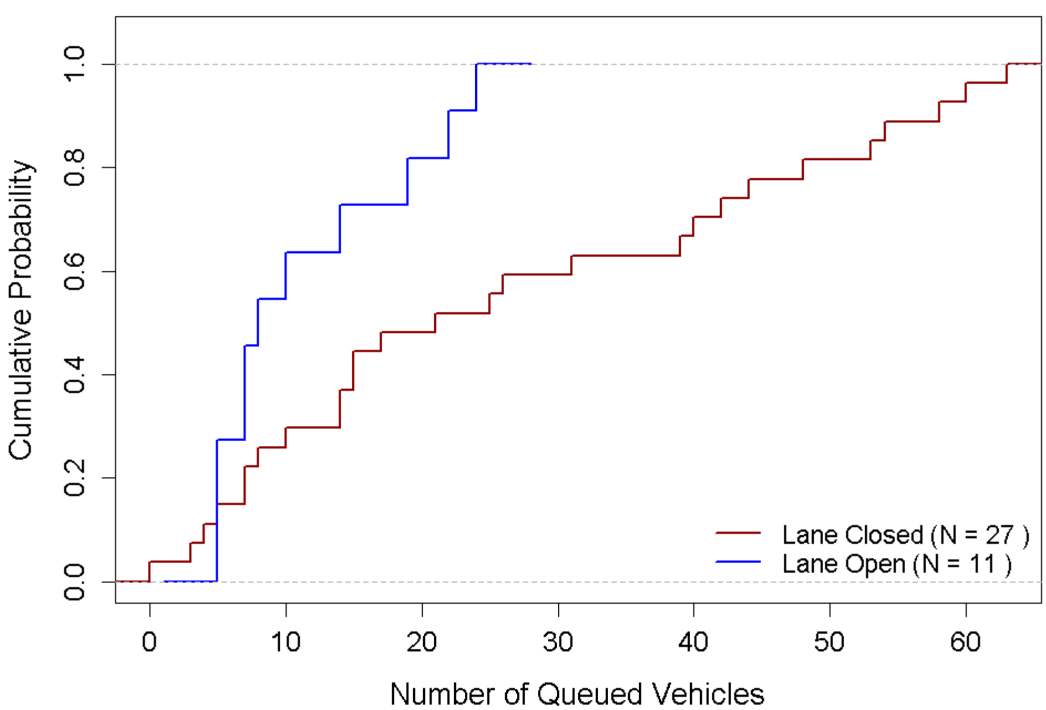


Figure 3: ECDFs of $PLNQV$ in the absence (lane open) and presence (lane closed) of construction

Clearly, the presence of a construction zone leads to a significant increase in the number of vehicles that queue in its vicinity. Such an increase associated with construction is expected to increase the queuing related safety hazard risk on the roadway. The determination of the resulting increase in risk is outside the scope of this study.

3.2.2 Queuing Related Safety Hazard "Hotspot" Identification

As mentioned above, imagery from bus-based cameras allows views of roadway conditions across spatially extensive roadway networks over time. As such, using the imagery can allow identification of both the location and timing of safety hazard "hotspots". The imagery obtained over the network of Figure 2 was used with the queue identification algorithm presented in section 2.2 to determine locations and times of queues on the day the data were collected, Oct. 31, 2024.

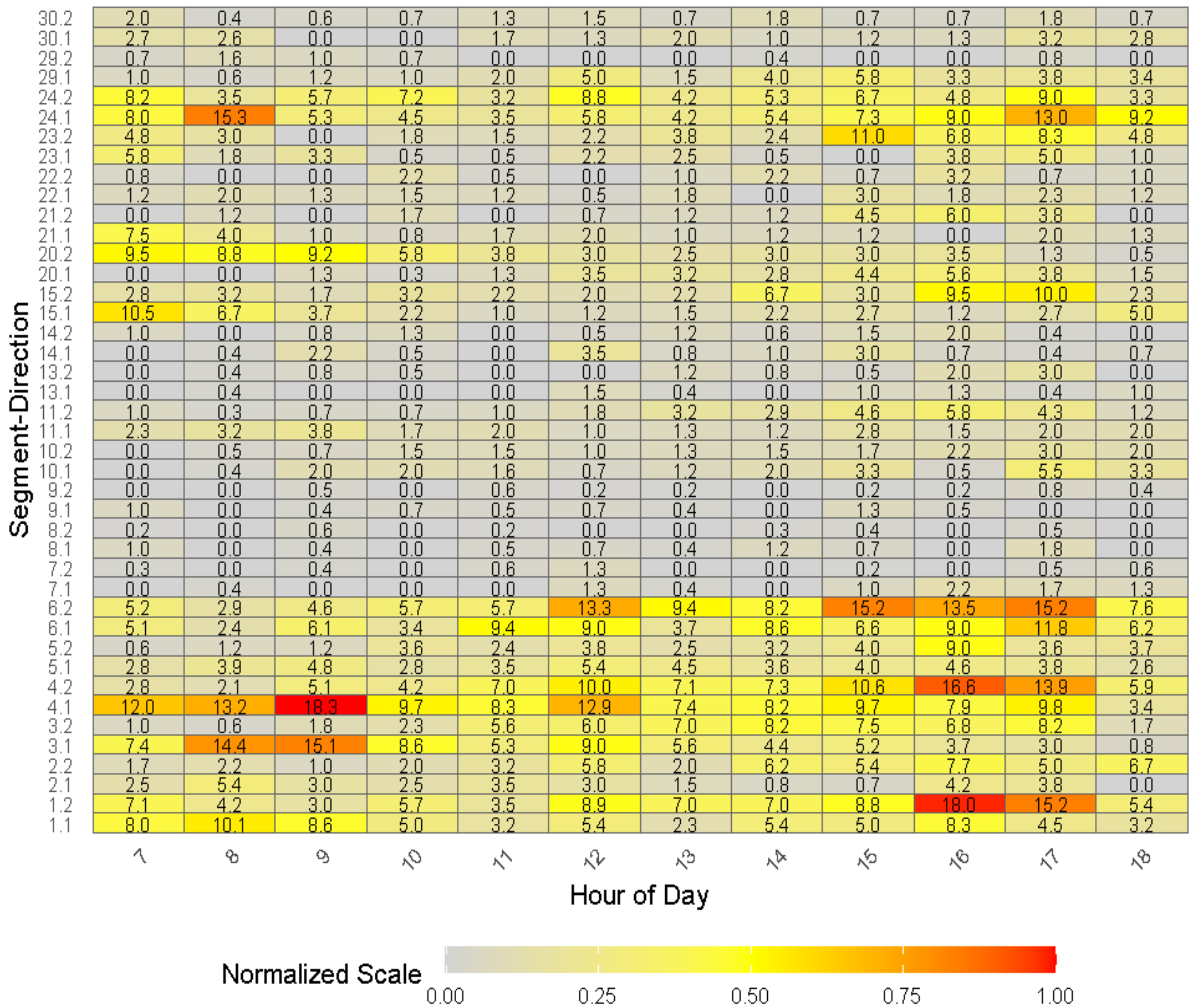
As discussed in section 2.2, an interarrival time between consecutive vehicles less than or equal to 2 seconds is used to identify queues, and V_{min} is set to 2 and 4. The values of NQV_i and NDQ_i were determined for each of the following hours of the day: 7:00-8:00, 8:00-9:00, … , 18:00-19:00.

Figure 4 (a) depicts a matrix of the values of NQV_i by hour for each segment-direction using V_{min} = 2, and Figure 4 (b) depicts a similar matrix using V_{min} = 4. The average number of queued vehicles for the segment-direction-hour are presented in the corresponding cell. In addition, for each segment-direction-hour *i* the relative value of NQV_i is computed. This relative value is denoted by $RVNQV_i$ and defined as follows:

$$RVNQV_i = \frac{NQV_i - NQV_{min}}{NQV_{max} - NQV_{min}} \quad (1)$$

where NQV_{max} and NQV_{min} are, respectively, the maximum and minimum average number of queued vehicles determined across all segment-direction hours. When using V_{min} = 4 (2), NQV_{max} = 15.4 (18.3), and NQV_{min} = 0 for both cases. The values of $RVNQV_i$ are used to form heatmaps from the segment-direction by hour-of-the-day matrices as shown in Figures 4 (a) and (b).

The NQV_{max} value stated above is greater when using V_{min} = 2 than when using V_{min} = 4, since vehicles identified as being in queues of two or three vehicles when using V_{min} = 2 would not be considered in queues for V_{min} = 4. For the same reason, the NQV values in the cells of Figure 4 (b) are greater than or equal to the values in the corresponding cells of Figure 4 (a). Note, too, that the cells in Figure 4 (b) that are "hotter" than yellow (i.e., orange or red) also appear as "hotter" than yellow in Figure 4 (a). As discussed in section 2.2, V_{min} = 2 is considered to be too loose of a value to identify queues in general, and these additional empirical comparisons lead to considering the results obtained with V_{min} = 4 in the following discussions.


Segment-Direction
30.2 2.0 0.4 0.6 0.7 1.3 1.5 0.7 1.8 0.7 0.7 1.8 0.7
30.1 2.7 2.6 0.0 0.0 1.7 1.3 2.0 1.0 1.2 1.3 3.2 2.8
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29.1 1.0 0.6 1.2 1.0 2.0 5.0 1.5 4.0 5.8 3.3 3.8 3.4
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24.1 8.0 15.3 5.3 4.5 3.5 5.8 4.2 5.4 7.3 9.0 13.0 9.2
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4.2 2.8 2.1 5.1 4.2 7.0 10.0 7.1 7.3 10.6 16.6 13.9 5.9
4.1 12.0 13.2 18.3 9.7 8.3 12.9 7.4 8.2 9.7 7.9 9.8 3.4
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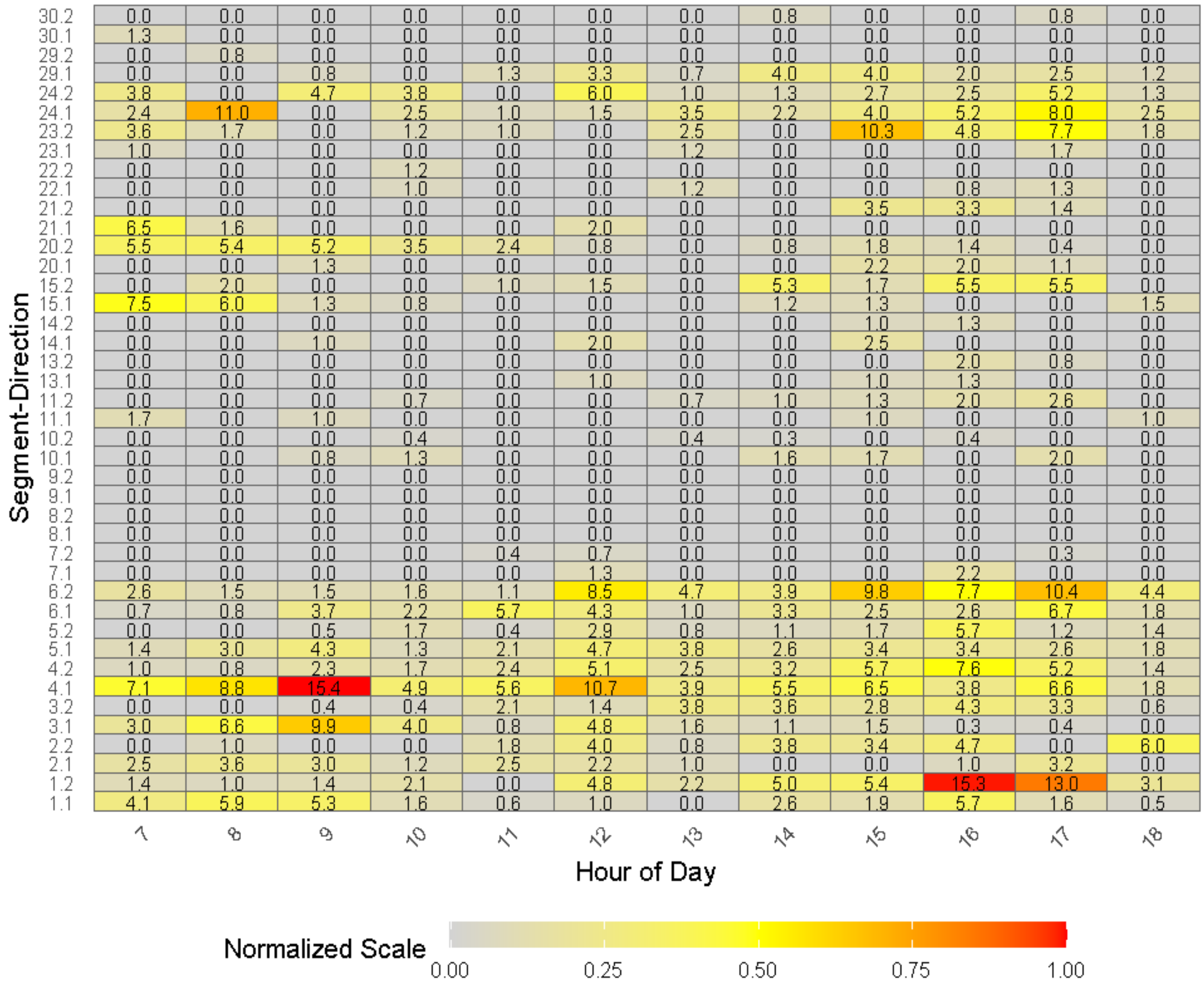
1.1 8.0 10.1 8.6 5.0 3.2 5.4 2.3 5.4 5.0 8.3 4.5 3.2
7 8 9 10 11 12 13 14 15 16 17 18
Hour of Day
Normalized Scale
0.00 0.25 0.50 0.75 1.00

(a): For $V_{min} = 2$



(b): For V_{min} = 4

Figure 4: Values of NQV by segment-direction-hour and heatmaps formed from $RVNQV$

The segment-direction-hours that have cells with $RVNQV_i$ > 0.5 (i.e., NQV_i > 7.7) in Figure 4 (b) are considered in the following discussion. The combinations of time and direction generally make sense for the identified segment-direction-hours. Specifically, recall that the X.1 directions indicate EB or NB traffic, and the X.2 directions indicate WB or SB traffic. Segment-directions 3.1, 4.1, and 15.1 are known to carry large amounts of inbound traffic and to exhibit important queuing at the intersection at the downstream traffic end of their segment-direction in the morning, whereas segment-directions 1.2 and 23.2 carry large amount of outbound traffic and exhibit important queuing at their downstream intersections in the late afternoon and early evening. Segment direction 24.1 is known to carry both inbound traffic in the morning and outbound traffic in the evening. Indeed, *ex post* analysis, the detailed presentation of which is beyond the scope of this report, indicates that the 8:00 to 9:00 and 17:00 to 18:00 hours – the two hours with NQV_i > 7.7 on this segment-direction – are the two hours with volumes (much) greater than volumes in other hours for this segment-direction.

The segment-directions identified were expected beforehand and, therefore, support the methodology. However, the specific hours where these segment-directions exhibited their largest amounts of queuing were only identified by the empirical analysis. Similarly, the identified queuing on segment-directions 4.1 during the noon hour is not surprising. Segment-direction 4.1 is known to carry inbound traffic in the morning and traffic returning from lunch or coming to campus for the first time after the lunch hour (in the later part of the 12:00 to 13:00 period). Segment-direction 3.1 would be expected to show similar patterns to those of 4.1. Although, $RVNQV_i$is not greater than 0.5 for 3.1 from 12:00 to 13:00 in Figure 4 (b) (when using V_{min} = 4), the NQV_i value in Figure 4 (a) (when using V_{min} = 2) would lead to $RVNQV_i > 0.5$. That is, there is likely the expected queuing on 3.1 from 12:00 to 13:00, but this queuing would tend to consist of multiple, shorter queues than on 4.1. Segment-directions 15.1 and 24.1, which stood out in the morning hours, mostly carry commuter traffic, with much less lunchtime traffic. Therefore, it is reasonable that these segment-directions do not stand out in the 12:00 to 13:00 period.

Identifying segment-direction 4.1 as the "hottest" segment-direction in the network from 12:00 to 13:00 is an interesting result determined from the use of bus-based video imagery collected over time across the network. Similarly, interesting results on segment-direction 6.2 are observed from the analysis. Segment 6 is a long segment with multiple pedestrian crosswalks. Queues are known to form in both directions throughout the day. It is not surprising that queuing is most pronounced from 12:00 to 13:00 and in the late afternoon and early evening, when many pedestrians cross segment 6 from classroom buildings south of the segment to dining facilities and dormitories north of the segment while vehicle volumes are high. However, the much more noticeable queuing on segment-direction 6.2 than on segment-direction 6.1 was not expected *a priori.* It is noted, though, that segment-direction 6.1 appears "hotter" at these times in Figure 4 (a), where V_{min} = 2 is used, than in Figure 4 (b), where V_{min} = 4 is used. That is, the pedestrian crosswalks do appear to also lead to queuing on segment-direction 6.1, but with shorter queues – two and three vehicles in length – than those that form on segment direction 6.2.

In addition to examining the average number of vehicles in queues, NQV_i, on each segment direction, as discussed in section 2.2 the average number of different queues on each segment-direction of the network, NDQ_i, is considered. As with the NQV analysis, the relative value of the number of different queues, $RVNDQ_i$, is determined for each segment-direction-hour as follows:

$$RVNDQ_i = \frac{NDQ_i - NDQ_{min}}{NDQ_{max} - NDQ_{min}} \tag{2}$$

where NDQ_{max} and NDQ_{min} are, respectively, the maximum and minimum average number of different queues determined across all segment-direction hours. (When using V_{min} = 4, NDQ_{max} = 2.0 and NDQ_{min} = 0.) A heatmap analogous to those presented for the average number of queued vehicles in Figures 4 (a) and (b) is presented in Figure 5 for the average number of different queues using V_{min} = 4. Again, the numerical value of the metric – average number of different queues in this case – in the segment-direction-hour is presented in each cell, and the colors of the heatmap are determined based on the $RVNDQ_i$ values.

As with the heatmap for the average number of queued vehicles (Figure 4), the heatmap for the average number of different queues (Figure 5) demonstrates that different segment-directions stand out as having more different numbers of queues but do so at only some hours of the day.

Again, considering cells with $RVNDQ_i$ > 0.5 (i.e., NDQ_i > 1.0), one notices that segment-direction 4.1 stands out in the morning and from 12:00 to 13:00 periods. Segment-direction 4.1 was indeed identified *a priori* as a segment direction where multiple queues would form (see section 3.2.1 and Mishalani, et al., 2024). The formation of these multiple queues in the morning and from 12:00 to 13:00 (return from lunch) are likely a result of the combination of infrastructure described in Section 3.2.1 and in Mishalani, et al. (2024) and the traffic patterns described above. Similarly, the multiple pedestrian crosswalks on segment-direction 6.2 (see above) would be expected to lead to multiple queues. The hours where there are noticeable average numbers of multiple queues (of four or more vehicles) align with the hours where the average numbers of queued vehicles are noticeable (also discussed above). In contrast to the results based on $RVNQV_i$ > 0.5, the 17:00 to 18:00 period stands out considering the number of queues. Nevertheless, it was at first surprising that there are no additional similarly noticeable average numbers of different queues during the times that stand out on segment-direction 6.1. However, the discussion above related to the shorter queues on segment-direction 6.1 is likely relevant for the numbers of different queues, as well.

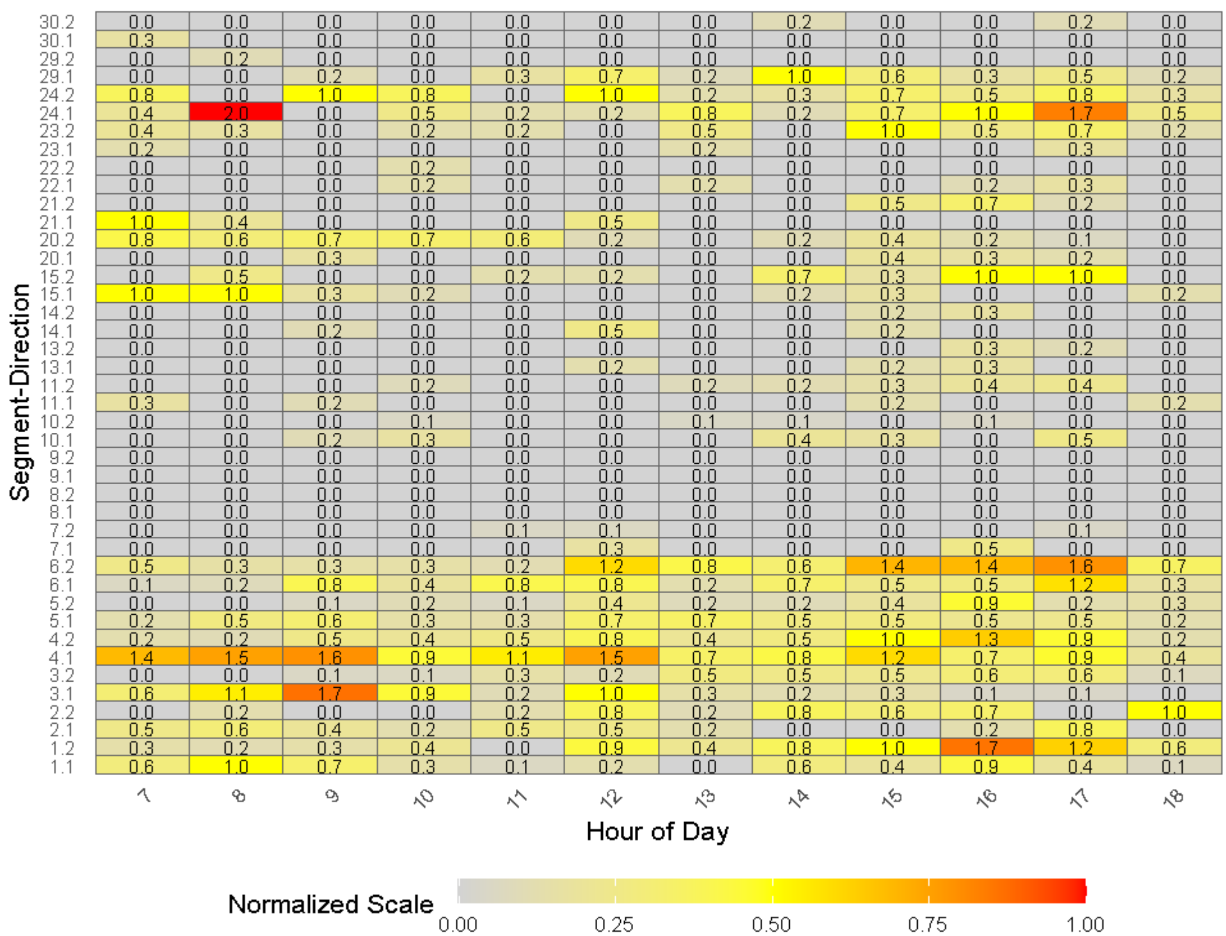


Figure 5: Values of NDQ by segment-direction-hour for V_{min} = 4 and heatmap

Similarly, the times when segment-directions 1.2 (16:00 to 18:00), 3.1 (8:00 to 10:00), and 4.2 (16:00 to 17:00) have $RVNDQ_i$ > 0.5 (NDQ_i > 1.0) correspond to inbound directions in the morning and outbound directions in the later afternoon and early evening. However, the existence of multiple queues on these specific segments – as well as the specific time-of-day-hours – was not known *a priori*, but rather was determined only after the application of the methodology. Segment-direction 24.1 stands out from 8:00 to 9:00 and from 17:00 to 18:00. This is another example of a segment-direction that was not known *a priori* to have multiple queues, but the timing of this "hotspot" is consistent with the timing of the noticeable number of queued vehicles on this segment-direction discussed above.

4. Education and Partner Outreach

Central to the focus of this project is the potential to take advantage of existing imagery obtained from video cameras deployed on transit buses in regular passenger service for purposes other than those for which the cameras are deployed. Doing so eliminates the sensor and platform costs associated with obtaining the imagery. It is worthwhile to impart this concept to the emerging generation of transportation engineers.

In addition to graduate and undergraduate students working on this project, this concept was presented in the following two OSU Civil Engineering courses during the period covered by this report:

- CIVILEN 5720 Transportation Engineering Data Collection Studies is an elective course that focusses on understanding, collecting, and processing traditional and emerging types of transportation data. Taking advantage of available bus-based video imagery is a central component of this course. The course, which was co-taught by two project PIs, was taken by 13 undergraduate students and 4 graduate students in Autumn semester 2024. In addition to presenting the concept in this course, as part of a course term project the students were trained to use the vehicle data extraction GUI and applied it to video imagery recorded by CABS buses on Oct 31, 2024. The extracted data were used in the investigations of this project.
- CIVILEN 3700 Transportation Engineering and Analysis is a required core course that all Civil Engineering undergraduate students take. The course introduces various traffic, transit, and roadway topics in a technical and analytical manner. One offering of this twice-per-year course was taught by one of the project PIs in Autumn semester 2024 and taken by 79 students. Another offering was taught by an instructor not associated with this project in Spring semester 2025 and taken by 59 students. In both offerings, the use of available bus-based video imagery for newly developed purposes is presented in a module on the OSU Campus Transit Lab.

This project relied on interactions with OSU's Transportation and Traffic Management (TTM). TTM oversees all campus transportation activities other than parking and traffic signal operations and owns and operates the Campus Area Bus Service (CABS). Longstanding relations between the project investigators and TTM led to TTM's providing the video imagery used in this project. The imagery was recorded by cameras mounted on CABS buses while in regular passenger service. The project investigators meet regularly with TTM management and staff to discuss various activities. The concept of identifying safety hazards and "hotspots" from TTM imagery was discussed during the period covered in this report, and future discussions are expected to increase the practical impact of the project's results and allow user grounded investigations.

5. Conclusion and Future Research

In this study where the OSU campus is used as a living lab testbed, the use of the available, repeated, and extensive imagery recorded by transit bus-mounted cameras for identifying queue presence and length related safety hazards along the roadways traversed by the buses is investigated. The increased presence of queues in association with construction zones is also explored. The results demonstrate the feasibility of the approach in identifying queuing over space, including around construction zones, and time.

It is important to develop a robust method to calibrate the threshold used to identity queues considering varying roadway segment conditions. Given that the automatic queue identification method relies on a GUI-based semi-automatic technique to identify vehicles passing camera-equipped buses in the opposite direction, for large-scale and efficient identification of safety hazard "hotspots" associated with recurrent queue formations, it is also important to develop an automatic machine vision method to replace the semi-automatic technique for identifying vehicles passing camera-equipped buses.

Similarly, it is important to consider other hazards, including the presence of heterogenous vehicles, speed variability, and overtaking. Speeds and their variation where autos conflict with vulnerable vehicles are also important safety factors.

Of course, the determination of the increased safety risk in the presence of the various traffic related hazards is also important. The ultimate impact of the research reported here will be the ability to determine the location and times of roadway traffic conditions that could compromise safety and to do so inexpensively across extensive urban networks by using an existing and widespread source of available data, namely, video imagery obtained from cameras mounted on buses in regular transit service. The ability to systematically determine and monitor hazardous roadway conditions would provide input to policymakers and designers developing measures aimed at reducing the likelihood and severity of traffic and traffic-related accidents.

References

Howarth, C.I., 1982. The Need for Regular Monitoring of The Exposure of Pedestrians and Cyclists to Traffic. *Accident Analysis and Prevention*, 14(5).

Jernigan, J.D., Lynn, C.W., 1995. *The Effect of Motorcycle Travel on the Safety and Operations of HOV Facilities in Virginia*, Final Report, Virginia Transportation Research Council, Virginia Department of Transportation, Federal Highway Administration.

MacCarley, C.A., 1997. Advanced Imaging Techniques for Traffic Surveillance and Hazard Detection. *Intellimotion*, 6(2), California Polytechnic State University, San Luis Obispo, California Department of Transportation.

Marlow, M., 1990. *Safety at Roadworks*, Report 351A, Swedish National Road and Transport Research Institute (VTI).

McCord, M.R., Mishalani, R.G., Coifman, B., 2020. *Using Municipal Vehicles as Sensor Platforms to Monitor the Health and Performance of the Traffic Control System*, Final Report, Mobility 21 University Transportation Center, US Department of Transportation, Washington, D.C., USA.

McCord, M.R., Mishalani, R.G., Shah, H., Coifman, B., 2023. *Determining Segment and Network Traffic Volumes from Video Imagery Obtained from Transit Buses in Regular Service: Developments and Evaluation of Approaches for Ongoing Use Across Urban Networks*, Final Report, Mobility 21 University Transportation Center, US Department of Transportation, Washington, D.C., USA.

McCord, M.R, Mishalani, R.G., Shah, H., 2025. VMT Monitoring of an Urban Network Using Bus-based Video Imagery: Empirical Evaluation and Comparison with LBS Data Derived Estimates. *Journal of Transportation Engineering, Part A: Systems*, 151(8): 04025063.

Mishalani, R.G., McCord, M.R, Shah, H., Redmill, K.A., 2004. *Monitoring of Urban Roadway Safety Hazards from Existing Bus-based Video Imagery*, Final Report, Safety 21 University Transportation Center, US Department of Transportation, Washington, D.C., USA.

Mollenhauer, M., White, E., Roofigari-Esfahan, N., 2019. *Design and Evaluation of a Connected Work Zone Hazard Detection and Communication System for Connected and Automated Vehicles (CAVs)*, Report, Safety through Disruption University Transportation Center (Safe-D), US Department of Transportation, Washington, D.C., USA.

Redmill, K.A., Yurtsever, E., Mishalani, R.G., Coifman, B., McCord, M.R., 2023. Automated Traffic Surveillance Using Existing Cameras on Transit Buses, *Sensors*, 23, 5086, https://doi.org/10.3390/s23115086.

Rezaei, M., 2014. *Computer Vision for Road Safety: A System for Simultaneous Monitoring of Driver Behaviour and Road Hazards*, Ph.D. thesis, The University of Auckland, New Zealand.

Rouphail, N.M., Jovanis, P.P., 1987. *Freeway Construction and Maintenance Zones: An Investigation of Accidents and Accident Reporting Systems in Illinois*, Final Report, Volume I, Illinois Transportation Research Consortium, Illinois Department of Transportation, Federal Highway Administration.

Still, M.L.; Still, J. D., 2019. Sharing the Road: Experienced Cyclist and Motorist Knowledge and Perceptions. *Advances in Intelligent Systems and Computing*, 964.

Tsai, Y., 2011. *Development of a Sensing Methodology for Intelligent and Reliable Work-zone Hazard Awareness*, Final Report, NCHRP-IDEA Program.

Yang, J.J., Wang, Y. Hung, C., 2018. *Monitoring and Assessing Traffic Safety at Signalized Intersections Using Live Video Images*, Report, Kennesaw State University, Georgia Department of Transportation, Federal Highway Administration.