Bicycle Queue Dynamics: Influence of Queue Density and Merging Cyclists on Discharge Rate at an Intersection

Maria J. Wierbos (*corresponding author*)
Delft University of Technology
Department of Transport & Planning
Stevinweg 1, 2628 CN Delft, The Netherlands
m.j.wierbos@tudelft.nl
+31 (0)15 278 3958

Bernat Goñi-Ros
Delft University of Technology
Department of Transport & Planning
Stevinweg 1, 2628 CN Delft, The Netherlands
b.goniros@tudelft.nl

Victor L. Knoop
Delft University of Technology
Department of Transport & Planning
Stevinweg 1, 2628 CN Delft, The Netherlands
v.l.knoop@tudelft.nl

Serge P. Hoogendoorn
Delft University of Technology
Department of Transport & Planning
Stevinweg 1, 2628 CN Delft, The Netherlands
s.p.hoogendoorn@tudelft.nl

November 14, 2017

Paper number 18-04044
Presented at 97th Annual Meeting of the Transportation Research Board, 2018

ABSTRACT

In many countries, an increasing number of people are using the bicycle for urban trips. The increased bicycle flow sometimes creates local congestion at intersections and demands better bicycle traffic management. To provide policy makers with models and advice on how to prevent congestion, an increased understanding of queue dynamics is required. This study analyzed the queue discharge process of cyclists at a controlled intersection, focusing on how queue density and merging cyclists influence the discharge rate. A bicycle equivalent (BE) value was introduced to correct for the impact of merging cyclists from different directions, with respect to the impact of cyclists in the original queue. For an intersection in Delft, the Netherlands, the discharge rate was found to increase for increasing queue density. Furthermore, cyclists who merged by overtaking were found to contribute more to the discharge rate compared to cyclists that were standing in the original queue. Cyclists that merged from a direction perpendicular to the queuing direction were found to hinder the discharge process, decreasing the observed outflow rate. These insights can be used as input for bicycle flow models to assess new plans for bicycle infrastructure and to develop measures to minimize delay at intersections.

1 INTRODUCTION

Bicycles are becoming increasingly popular as a way of transport, especially in regions with a positive policy towards cycling (*1*). Around 27% of all daily trips in the Netherlands were made by bicycle between 1995 and 2005 (*2*). This percentage hardly changed in the period between 2005 and 2015, but people indicated that the distance traveled per trip had increased, leading to more cyclists on the roads (*3*) (*4*). The increased bicycle traffic causes local congestion at intersections, even though the Dutch cycling infrastructure is well developed. Little is known about the dynamics of bicycle flow and more research is required to identify measures that can help prevent future bicycle congestion.

This study focuses on the queue dynamics at a controlled intersection to gain insight into the factors that influence the queue discharge rate, such as queue density. Cyclists have a large freedom in choosing their exact position on the road, especially when they join a queue. Depending on how compact the people position themselves, a bicycle queue can have different densities. When moving, the density relates to flow according to the fundamental diagram in traffic flow theory. If and how such a relation holds for queue density and queue outflow is open to question.

Furthermore, it is unclear how so-called "merging cyclists" affect the outflow (see Figure 1). These merging cyclists are additional cyclists that merge into the flow during the queue discharge process for example, by overtaking the queue from behind, or joining the queue from a side. The influence of merging cyclists are linked to the layout of the intersection and number of approach directions. If there are enough open spaces in the queue to absorb the additional cyclists, the merging behavior might have a positive effect on the overall flow. However, if the merging behavior obstructs the queue discharge process, the overall impact might be negative. This leads to the following research question: What is the impact of queue density and merging cyclists on the queue discharge rate at intersections?

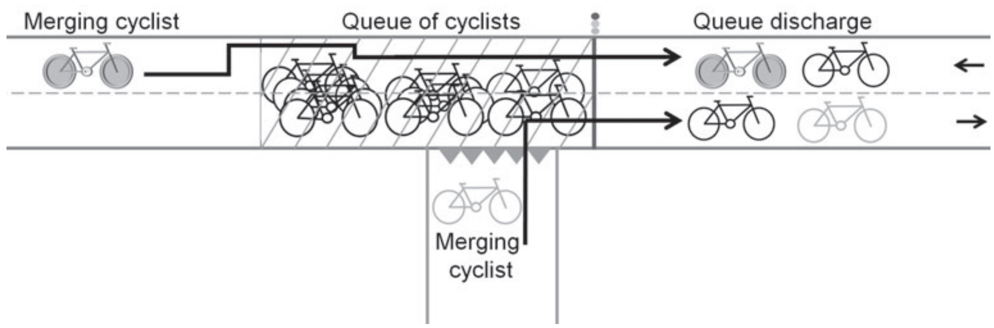


FIGURE 1 Sketch of a queue discharge process: the original queue is indicated by the black cyclists in the hatched area, the black arrows indicate merging cyclists who skip part of the queue and join the discharge before the queue is cleared.

This study analyzes empirical data of an intersection with multiple approach directions in Delft, the Netherlands. Linear regression analysis is used to quantify the influence of queue density and merging cyclists on the queue discharge rate. This knowledge can be used to evaluate existing infrastructure with respect to cyclist delay, or to design new intersections where the delay for cyclists is reduced. The results will be of interest especially for countries with high bicycle volumes, such as the Netherlands. The paper is structured as follows: Section 2 provides background information on bicycle traffic flow and equivalent units, Section 3 describes the research methodology, Section 4 describes the case study which is used to analyze the queue discharge process, Section 5 shows the results of the analysis, and finally, Section 6 discusses the conclusions of this study.

2 BACKGROUND

2.1 Bicycle flow dynamics

Cyclists have a large freedom to choose their exact position on the road, since a bicycle lane is generally wider than the bicycle itself. This enables cyclists to overtake other people or to cycle in pairs (*5*). At intersections, this increased freedom leads to queues which are less organized than the queues in motorized traffic. A queue of motorized vehicles is structured in lanes, whereas cyclists in a queue are grouped closely together and form a cluster pattern (*6*).

The flow characteristics of bicycle and motorized traffic are comparable under certain conditions (*7*). Similar concepts such as speed, flow and density relations can be used to describe the flow on a macroscopic level (*8*). Typical characteristics are among others, capacity, critical density, and jam density. Only a few values have been reported on jam density, all varying around 0.6 cyc/m^2 (*7*) (*9*). Navin (*7*) performed the first experiments in 1974 in Vancouver (Canada) and compared the findings to data from real-life situations, resulting in an estimated capacity of about 4,000 cyc/h/m for a 2.5m wide cycle path. Botma and Papendrecht (*5*) studied bicycle data in The Netherlands, estimating a capacity between 2,600 and 3,600 cyc/h/m for a 2.5m wide cycle path. Hoogendoorn and Daamen (*10*) found a theoretical capacity value of 1,531 cyc/h/m but indicated that this value may be an overestimation of the actual capacity. A capacity of around 3,300 cyc/h/m was found at a critical density of 0.102 cyc/m^2 by Li et al. (*11*), who observed mixed bicycle traffic consisting of around 80% electric bicycles.

The maximum flow at intersections can be described by either saturation flow or capacity. The saturation flow is the maximum number of cyclists that pass the stop line of the intersection within a unit of time, whereas the capacity takes into account the signal time of an intersection, resulting in a lower value than saturation flow (*12*). Seriani et al. (*13*) analyzed the saturation flow at Travistock Square (Londen, UK) and Pocuro (Santiago de Chile). The saturation flow at Travistock Square depended on the time of day; the maximum of around 4,300 cyc/h/m was observed in morning peak hour, while the results were 25% lower for the afternoon peak hour. A near linear relation for lane width was found at Pocuro, ranging between 2,000 cyc/h/m on a 1m lane and 2,350 cyc/h/m on a 2m lane. Jin et al. (*14*) also found that the width of a cycle path did not significantly influence the capacity per meter, implying that the total capacity of a cycle path scales linearly to the width of the cycle path. The time interval used to calculate capacity was found to influence the results significantly and with a linear downward trend; the estimated capacity decreased when a larger time interval was used for the estimation.

Bicycle queue formation has been studied by Cao et al. (*15*) which resulted in two models to describe the relation between queue length, queue density and density distribution. It was observed that initially only a portion of the lane width was used for the queue, but when a critical queue length was reached, the additional cyclists would overtake the queue and start to fill the gaps. This process indicates that queues of similar lengths can have different average queue densities.

No previous research was found that describes the discharge process of a bicycle queue, connecting density to queue discharge rate. Identifying such relation can be useful for optimizing bicycle flow at intersections. The high variety in reported capacity and saturation flow might be explained by several factors such as infrastructure design, weather conditions and heterogeneity in bicycle or bicyclist type. Equivalent unit can be used to account for some of this heterogeneity and will be addressed next.

2.2 Equivalent units for heterogeneous flow

The traffic flow at an intersection with multiple approach directions can be considered as heterogeneous, since the overall flow consists of multiple sub flows with different characteristics. This heterogeneity makes it difficult to compare flow characteristics such as queue discharge rate. The comparison is easier when the impact of different factors are described in the same reference unit. The most common reference is the passenger car equivalent (PCE), which was first introduced by the 1965 Highway Capacity Manual (*16*). Each vehicle type has a specific correction factor (PCE value) to convert a mixed traffic stream into a uniform flow of PCEs.

Alternative reference modes have been proposed as well to retrieve a homogeneous description of heterogeneous flow. Cao and Sano (*17*) for example, proposed a motorcycle equivalent (ME) to translate mixed traffic conditions in Hanoi (Vietnam) into a unified motorcycle flow. A mixed flow of bicycles and mopeds was normalized in bicycle equivalents (BE) units by Chen et al. (*18*). It was found that mopeds have a BE value larger than one under high-density conditions, and a BE value smaller than one under low-density conditions. Other research focused on retrieving BE values for different infrastructure and varying mixing ratios for motorized and non-motorized cyclists. The BE value for mopeds was to be dependent on lane width, slope of the road, density and moped percentage (*19*).

The impact of electrical bicycles on bicycle flow is described by Jin et al. (*14*), who analyzed mixed bicycle flow under free flow, stable and restricted flow conditions. A mean bicycle equivalent value of 0.666 was found for the electric bicycle, which was used to calculate capacity for different compositions of the mixed flow. Equivalent units have not been used before to describe bicycle flow at an intersection with multiple approach directions. Applying this concept to merging cyclists is a promising method to capture the influence of merging cyclists to the queue discharge rate.

3 METHODOLOGY

When there are more cyclists in a queue, it will take longer time before the queue is cleared. However, other factors might also influence the queue discharge process such as queue density and merging behavior (Figure 1). To investigate this relation, this study proposes a method to analyze the queue discharge process based on a fixed queue length. Section 3.1 studies the influence of queue density to the discharge time. Section 3.2 extends the model to include the effect of merging cyclists.

3.1 Influence of queue density on discharge rate

The density of a queue depends on its dimensions and the number of cyclists in it. For a queue of fixed length, a waiting area can be defined as the length multiplied by the width of the cycle path. The queue density is then calculated by the number of cyclists in the waiting area (N_q) divided by the fixed dimensions of the waiting area (A). The duration of the queue discharge process is the discharge time, which is the time interval between the first and the last cyclist in the queue to exit the waiting area.

A regression analysis can be performed if a linear relationship is assumed between discharge time (T_{dis}) and queue density (k_q). This results in the following regression equation:

$$T_{\text{dis}} = T_0 + \beta_1 k_q. \tag{1}$$

Here, β_1 is the regression coefficient, and T_0 is the regression constant for discharge time. The value for T_0 can be interpreted as the minimum amount of time in which the last cyclist in the queue (of fixed length) can exit the waiting area. The term $\beta_1 k_q$ can be explained as the penalty for crowded conditions: The more cyclists in the waiting area, the higher the queue density, and the larger the discharge time. The goodness of fit of the model is tested by determining the R-squared values and hypothesis testing. The F-test is used to check the significance level of the overall model fit, whereas the student's t-test is performed to check the statistical significance of the regression parameters.

The queue discharge rate (q_{dis}) is the number of cyclists (N) that pass the exit line of the waiting area during the discharge time:

$$q_{\text{dis}} = \frac{N}{T_{\text{dis}}}. \tag{2}$$

Here, N is the sum of the number of cyclists in the queue (N_q) and the additional cyclists that merge into the queue during the discharge process. If the merging cyclists influence the queue discharge process, the discharge time will be affected and so will the queue discharge rate. Due to the possible correlation between discharge time and total cyclist count, the regression analysis is not performed directly to discharge rate but indirectly via the queue discharge time.

Estimating discharge time in equation 1 only takes the queue density into account and does not include the effect of merging cyclists. An extension of the model that does include this is proposed in Section 3.2.

3.2 Influence of merging cyclists

A multiple linear regression analysis on the discharge time can quantify the affect of merging cyclists as well as queue density. To have identical units for all variables, density is now expressed as number of cyclists in the queue, resulting in the following expression:

$$T_{\text{dis}} = T_0 + \mu N_q + \sum \alpha_i N_i. \tag{3}$$

Here N_q is the number of waiting cyclists in the queue, N_i is the number of cyclists merging into the queue from direction i, T_0 is the regression constant, and μ and α_i are the regression coefficients. The regression coefficients of the different merging directions are tested on a 95% significance level and only the directions that lead to the model with the highest adjusted R-squared value should be included. The standardized regression coefficients of the final model are used to evaluate and rank the influencing factors for discharge time. A standardized coefficient is expressed in standard deviations (σ) and indicates how many standard deviations the discharge time will change due to the increase of one standard deviation of the independent variable.

Scaling the regression coefficients (α_i) to the main influencing factor (μ) gives an indication of the impact of the different influencing factors. This process of scaling is similar to the concept of passenger car equivalent, which is a measure for the impact factor of different classes in heterogeneous (motorized) traffic (*20*). For bicycle traffic, a bicycle equivalent (BE) is introduced as a measure for the impact of merging cyclists from direction i relative to the impact of the cyclists in the original queue:

$$\mathrm{BE}_i = \frac{\alpha_i}{\mu}. \tag{4}$$

The bicycle equivalent value BE_i represents the impact that a merging cyclist from direction i has on the discharge time. A BE value larger than 1 indicates that the merging cyclist has an increased impact on the discharge time, hindering the waiting people more than if the cyclist were standing in the original queue. A BE value smaller than 1 indicates that the merging cyclist has less influence than if they were standing in the waiting area.

Using the BE values, the total number of cyclists in equation 2 can be recalculated to the reference unit or bicycle equivalent units (beu). This results in a uniform expression for queue discharge rate in beu/s,

$$q_{\text{beu}} = \frac{N_{\text{beu}}}{T_{\text{dis}}} = \frac{N_q + \sum(\mathrm{BE}_i N_i)}{T_{\text{dis}}}. \tag{5}$$

Merging cyclists with BE value larger than 1 indicates that the overall influence on the outflow rate in cyc/s is negative. The negative impact on discharge time is larger than the positive gain of an additional cyclist in the total cyclist count N. After correcting for this impact, their contribution changes to positive in the queue discharge rate expressed in beu/s. Merging cyclists with a BE value smaller than 1 results in a positive influence to the outflow rate when expressed in cyc/s but this influence is reduced when the outflow rate is expressed in beu/s.

4 CASE STUDY

The methods described in Section 3 were tested in a case study for which the data was collected in October 2014, see (*10*). The location is the Mekelweg−Jaffalaan - intersection, which is part of a busy cycling route between the city center and the university campus in Delft, the Netherlands. Video data were collected over a period of 2 weeks, covering an intersection where bicyclists have priority over cars. The stream of cyclists in morning peak hour was controlled by human traffic controllers who stopped the stream of cyclists periodically to help car traffic cross the cycle path. An overview of the situation is provided in Figure 2. Due to the proximity to the university, the flow consisted predominantly of students who cycled on a regular basis and might have been rushed to get to class.

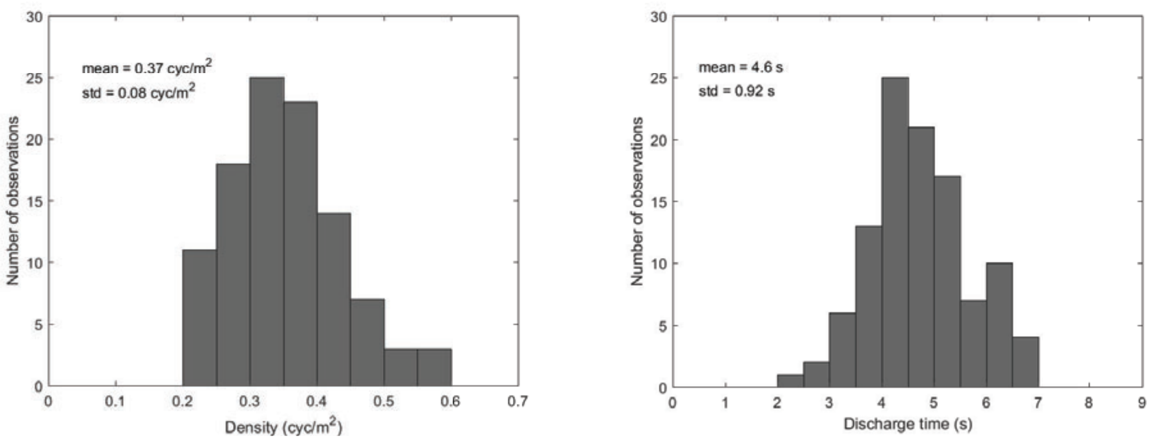
The video was analyzed, looking specifically at the moments at which the bicyclists were stopped and released again by the traffic controller. During the blocked periods, a queue of cyclists formed in front of the intersection using occasionally the full width of the cycle path (3 meter), including the lane for the opposite direction. In the images, a waiting area was defined and drawn by the white lines in Figure 2b. The size of the waiting area (A, 6.7m x 3m) was chosen such that a clear count of the number of cyclists could be made based on the video images, so its size was limited by the presence of the tree. The events were recorded only when the queue length reached the end of the waiting area or exceeded this length, resulting in a total of 106 queuing events. The number of cyclists within the waiting area was determined manually, resulting in different queue densities depending on how compact the cyclists had positioned themselves. After the traffic controller released the flow, the queue discharge time was determined as the time interval between the first wheel passing the exit line and the second wheel of the last cyclist (of the original queue) passing the exit line. With this method, the initial start-up time of the cyclists was not included in the discharge time. The bicyclists did not have any interaction with vehicles during the queue discharge time, and interaction with pedestrians was very limited. Based on this knowledge, we assumed in the analysis that the queue discharge process was only influenced by cyclist-cyclist interaction.

The observed queue density ranged between 0.2 and 0.6 cyc/m^2 with a mean of 0.4 cyc/m^2 and standard deviation of 0.086 cyc/m^2, see figure 3. The time to empty the waiting area ranged from 2 to 7 seconds with a mean of 4.6 s and standard deviation of 0.92 s. Before the last cyclist of the original queue left the waiting area, additional cyclists could merge into the queue from different directions. The merging cyclists were counted from three different directions (see Figure 2b) being the cycle path from the Jaffalaan which has a 90 degree angle with the waiting area (1), overtaking from behind (2) and a shortcut direction across the side walk (3). Furthermore, the presence of cyclists going in the opposite direction was recorded (4) as well as the cyclists coming from direction 5. Only the queues in the morning peak hour were captured and analyzed. At that time of the day, the majority of the flow was directed towards the university building (to the right in Figure 2) and almost no oncoming cyclists were present coming from direction 4. The number of additional cyclists per discharge period varied between $0-6$ cyclists for direction 1, $0-4$ cyclists for direction 2, and $0-2$ for direction 3. During the selected queuing events, no bicyclists were observed coming from direction 5.

(a) Example of queuing event, the cyclists within the two white lines are counted to determine queue density.

(b) Influencing directions

FIGURE 2 Example of the video data (a) with the waiting area defined by the white lines. The black arrows indicate the different directions in which additional cyclists can influence the queue discharge process (b).



(a) Frequency distribution of queue density

(b) Frequency distribution of queue discharge time

FIGURE 3 Frequency distributions

5 RESULTS

The results of the analysis of the case study data are discussed, starting with the influence of queue density on the queue outflow rate, followed by a quantification of the influence of merging cyclists, which leads to queue discharge rate expressed in bicycle equivalent units.

5.1 Influence of queue density

The observed queue discharge times are plotted against queue density in Figure 4. The scattered dots show a positive trend, which is captured by the linear fit. The results show that discharge time increased gradually with queue density, which can be interpreted as a time penalty for crowdedness. The six lines in Figure 4 that start at the origin represent lines of fixed flow rate, ranging from 0.5 to 3.0 cyc/s. The slope of these lines are equal to A/q with A the area of the waiting area (constant value) and q the different flow rates. Although the data points are scattered, the overall trend is that lower queue density corresponded to lower queue discharge rates and higher queue density led to larger values for queue discharge rate. This indicates that the discharge rate increased with increasing queue density. Linear regression analysis results in the following regression model:

$$T_{\text{dis}} = 2.70 + 5.05k_q, \tag{6}$$

with an R-squared value of 0.226. Although the p-value of the F-test confirm with 95% confidence that the influence of queue density is significantly different from zero, the R-squared value indicates that the equation explains only little of the variance in observed discharge time.

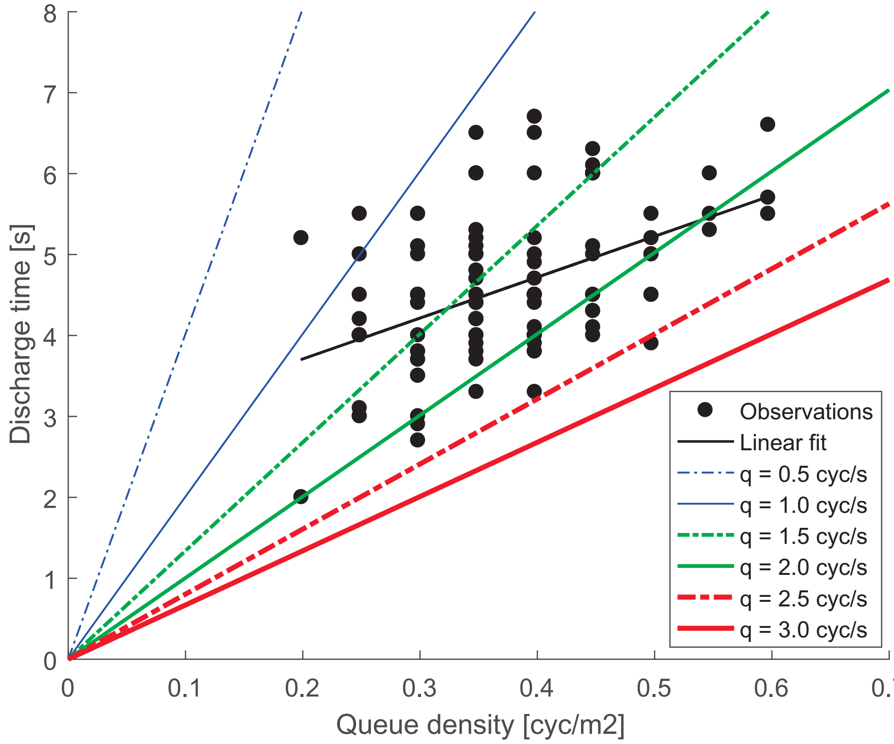


FIGURE 4 Observed discharge time and queue density (dots) and the linear regression fit (black line). The lines starting from the origin indicate different flow rates in cyc/s over the full width of the cycle path (3 meter).

5.2 Influence of merging cyclists

Other explanatory factors for the observed variation in queue discharge time are cyclists that merged into the queue during the discharge process. The multiple regression analysis showed that only the number of waiting cyclists in the queue (N_q), number of merging cyclists from direction 1 (N_1) and merging cyclists from direction 2 (N_2) had a significant influence on the discharge time. The influence of merging cyclists from direction 3 (N_3) and oncoming cyclists (N_4) was not statistically significant and has therefore been excluded from the final regression analysis. Table 1 provides the results of the Pearson correlation. It shows that the correlation between discharge time and both N_q and N_1 are around 0.50, indicating that these variables had a moderate and positive impact on the discharge time. The correlation between discharge time and merging cyclists from direction 2 is lower, around 0.25, indicating that N_2 had a possible positive impact on discharge time, but the connection was weak. The correlation between N_q and N_1, N_q and N_2 and N_1 and N_2 is smaller than 0.20, indicating that the relation was very weak and that the variance of one variable was unlikely to explain the variation of the other variable. The p-values of the correlation results are shown in Table 2. The values below 0.05 are statistically significant, meaning it is 95% certain that the variations in both variables are not unrelated. In other words, the variables N_q, N_1 and N_2 were likely to explain a part of the variance within the observed queue discharge time.
The regression model that fits the data best is captured by the following equation:

$$T_{\text{dis}} = 2.06 + 0.24N_q + 0.32N_1 + 0.20N_2. \tag{7}$$

The standardized regression coefficients for N_q, N_1 and N_2 are respectively 0.46, 0.44 and 0.21 indicating that the number of waiting cyclists in the queue was the variable that explained most of the variation in discharge time, closely

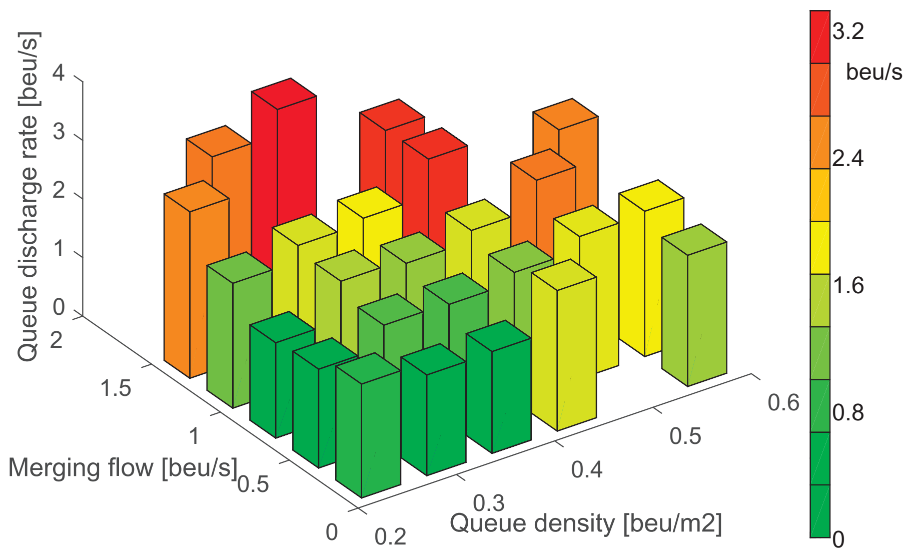


FIGURE 5 Queue discharge rate at different queue density and merging flow, expressed in bicycle equivalent units.

TABLE 1 Pearson correlation matrix

	T_{dis}	N_q	N_1	N_2
T_{dis}	1	-	-	-
N_q	0.476	1	-	-
N_1	0.515	0.065	1	-
N_2	0.261	-0.045	0.184	1

TABLE 2 P-values of the correlations

	T_{dis}	N_q	N_1	N_2
T_{dis}	1	-	-	-
N_q	0.000	1	-	-
N_1	0.000	0.508	1	-
N_2	0.007	0.648	0.059	1

followed by the number of merging cyclists from direction 1. As a result, similar queue discharge times were observed for different combinations of queue density and merging cyclists. The R-squared value of the regression equation is 0.498, indicating that about 50% of the variance in discharge time was explained by the model.

The regression model for discharge time shows that the influence of merging cyclists depended on the direction of the merge. The impact of the merging direction with respect to the influence of the queue density was captured by the bicycle equivalent (BE) value. A BE value of 1.31 was found for bicyclists that merged by taking a sharp turn ($\sim$90 degree angle, direction 1) and a BE of 0.83 was found for cyclists that overtook from behind (direction 2).

Using the BE values, the effect of merging cyclists from different directions was recalculated to a uniform expression for merging flow, expressed in bicycle equivalent units. The results are visualized in Figure 5, showing an increase in queue discharge rate with both increasing queue density and corrected merging flow. The observed queue discharge rate ranged between 1.3 and 3.3 cyc/s over a 3 meter wide cycle path, which translates into 1,500 to 4,200 beu/h/m. These estimates were valid only during the discharge process itself, which lasted up to 7 seconds in this study. It is unlikely that this high flow can be maintained for a full hour in real traffic conditions, but for comparison reasons the rates were extrapolated to an hourly rate. The large variation in queue discharge rate was explained by different combinations of queue density and merging cyclists. The lower values were related to low queue density values and low merging flow rate, whereas the highest queue discharge values were achieved by a high presence of merging cyclists. The maximum value of 4,200 beu/h/m was found at a queue density of 0.4 cyc/m^2 and merging flow of 1.75 beu/s.

6 DISCUSSION AND CONCLUSION

This study analyzed the queue discharge process of cyclists at a controlled intersection, focusing on how queue density and merging cyclists influence the discharge rate. Merging cyclists are cyclists that skip part of the original queue (by overtaking or merging from the side) during the discharge process. For a specific intersection in Delft, the Netherlands, video data of in total 106 queuing events were analyzed, looking specifically at the queue discharge time, the number of cyclists in the queue and the number of cyclists that merge during the discharge time.

Using linear regression analysis, a model was estimated to predict the queue discharge rate. Within the density range of 0.2 to 0.6 cyc/m^2, the queue discharge rate increased with increasing queue density, indicating that a higher discharge flow can be obtained if cyclists create a dense queue. Further analysis to discharge time identified three factors that influenced the time for clearing a queue of fixed length, being the number of cyclists in the queue, merging cyclists from the side, and merging cyclists from behind. It was found that merging behavior from the side disrupted the discharge process and caused a delay to the last cyclist in the original queue, whereas merging behavior from behind affected the discharge time less.

A method to calculate a bicycle equivalent (BE) value was introduced to correct for the impact of merging cyclists from different directions, with respect to the impact of cyclists in the original queue. Using the BE values, a uniform expression for discharge rate was retrieved, independent of the different approach directions. A cyclist with BE value smaller (resp. larger) than 1 indicates that the contribution to the measured outflow rate was higher (resp. negative) than if they were standing in the original queue. The direction-specific BE values were used to calculate the theoretical capacity of a bicycle intersection with different approach directions, which is of interest for the design and evaluation of (new) cycling infrastructure.

It was found that cyclists who merged by overtaking contributed more to the observed discharge rate compared to cyclists that were standing in the original queue. Cyclists that merged from a direction perpendicular to the queuing direction were found to hinder the discharge process, decreasing the observed discharge rate. After correcting the observed discharge rates using the BE values, a maximum of 4,200 beu/h was found. This value was found at a queue density of 0.4 cyc/m^2 and merging flow of 1.75 beu/s.

Future research could investigate if the increase of discharge rate with queue density is also valid for queue densities higher than 0.6 cyc/m^2 and at which point this effect is maximized. The effect of infrastructure design could be studied, such as width of the cycle path, and interaction with other modes. Allowing for a dynamic queue length instead of a fixed length would be interesting, as well as analyzing the exact spatial configuration of the queue to identify the relation to the merging flow. Open spaces in the queue (local density minima) could initiate merging behavior from different directions. Personal characteristics (i.e. age, gender, level of fitness) can be included to retrieve a more specific impact factor for merging cyclists.

The results of this study contributes to the development of bicycle models which help in assessing new plans for bicycle infrastructure layout or measures to minimize delay at intersections.

ACKNOWLEDGEMENTS

This research was supported by the ALLEGRO project (Unraveling slow mode traveling and traffic: with innovative data to create a new transportation and traffic theory for pedestrians and bicycles), which is financed by the European Research Council and Amsterdam Institute for Advanced Metropolitan Solutions.

REFERENCES

[1] Heinen, E., B. van Wee, and K. Maat, Commuting by Bicycle: An Overview of the Literature. *Transport Reviews*, Vol. 30, No. 1, 2010, pp. 59–96.
[2] Pucher, J. and R. Buehler, Cycling for Everyone: Lessons from Europe. *Transportation Research Record: Journal of the Transportation Research Board*, Vol. 2074, 2008, pp. 58–65.
[3] Centraal Bureau voor de Statistiek, *Personenmobiliteit in Nederland; vervoerwijzen en reismotieven*, 2016.
[4] KiM, Mobiliteitsbeeld 2016, 2016.
[5] Botma, H. and H. Papendrecht, Traffic Operation Of Bicycle Transporting. *Transportation Research Record: Journal of the Transportation Research Board*, Vol. 1320, 1991, pp. 65–72.

[6] Wang, J. and H. Wei, Traffic Segregation on Spatial and Temporal Bases: The Experience of Bicycle Traffic Operations in China. *Transportation Research Record: Journal of the Transportation Research Board*, Vol. 1396, 1993, pp. 11–17.
[7] Navin, F. P. D., Bicyce Traffic Flow Characteristics: Experimental Results and Comparisons. *ITE Journal*, Vol. 64, No. 3, 1994, pp. 31–37.
[8] Zhang, J., W. Mehner, E. Andresen, S. Holl, M. Boltes, A. Schadschneider, and A. Seyfried, Comparative Analysis of Pedestrian, Bicycle and Car Traffic Moving in Circuits. *Procedia - Social and Behavioral Sciences*, Vol. 104, 2013, pp. 1130–1138.
[9] Deng, X. H. and J. Xu, Study on bicycle flow characteristics at intersections. In *Civil Engineering and Urban Planning III* (Mohammadian, Goulias, Cicek, Wang, and Maraveas, eds.), Taylor & Francis Group, London, 2014, pp. 393–399.
[10] Hoogendoorn, S. P. and W. Daamen, Bicycle Headway Modeling and Its Applications. *Transportation Research Record: Journal of the Transportation Research Board*, Vol. 2587, 2016, pp. 34–40.
[11] Li, Z., M. Ye, Z. Li, and M. Du, Some Operational Features in Bicycle Traffic Flow. *Transportation Research Record: Journal of the Transportation Research Board*, Vol. 2520, 2015, pp. 18–24.
[12] Chen, X., K. An, and L. Li, Study on the Influencing Factors of Bicycle Lane Capacity. In *Transportation Research Board*, Transportation Research Board, Washington D.C., 2014.
[13] Seriani, S., R. Fernandez, and E. Hermosilla, Experimental study for estimating capacity of cycle lanes. *Transportation Research Procedia*, Vol. 8, 2015, pp. 192–203.
[14] Jin, S., X. Qu, D. Zhou, C. Xu, D. Ma, and D. Wang, Estimating cycleway capacity and bicycle equivalent unit for electric bicycles. *Transportation Research Part A: Policy and Practice*, Vol. 77, 2015, pp. 225–248.
[15] Cao, J., R. Liu, and B. Li, Research on the Bicycle Flow in Signalized Intersections with Video-based Detection Technologies. In *ICTIS 2011*, American Society of Civil Engineers, Reston, VA, 2011, pp. 629–635.
[16] Roess, R. . P. and E. . S. Prassas, *The Highway Capacity Manual: A Conceptual and Research History*, Vol. 5 of *Springer Tracts on Transportation and Traffic*. Springer, 2014.
[17] Cao, N. Y. and K. Sano, Estimating Capacity and Motorcycle Equivalent Units on Urban Roads in Hanoi, Vietnam. *Journal of Transportation Engineering*, Vol. 138, No. 6, 2012, pp. 776–785.
[18] Chen, X., H. Han, J. Ye, S. Ma, and Y. Xu, Normalized Volume Measurement for Nonmotorized Traffic Flow Mixed with Mopeds. *Transportation Research Record: Journal of the Transportation Research Board*, Vol. 2239, 2011, pp. 9–15.
[19] Chen, X., H. Han, and B. Lin, Developing Bicycle Equivalents for Mopeds in Shanghai, China. *Transportation Research Record: Journal of the Transportation Research Board*, Vol. 2317, 2012, pp. 60–67.
[20] Transportation Research Board, *Highway Capacity Manual*. National Research Council, Washington, DC., 2000.