Gained Distance-Headway in a Bicycle Queue at a Signalized Intersection

CTB3000 Bachelor End Project Report
TU Delft Faculty of Civil Engineering

J.A.L (Jesse) Groenewegen
4378407

Supervisors: Dr. Ir. Y. Yuan
Dr. Ir. A.M. Salomons

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Summary

Currently, there is not much known about the flow characteristics of cyclists in bicycle lanes, especially compared to what is known about flow characteristics for motor vehicle traffic [Goñi-Ros et al., 2018]. Without the proper knowledge of these flow characteristics, bicycle traffic management has less tools to improve bicycle traffic. Given that bicycle traffic differs from motor vehicle traffic, for instance with respect to individual size and speed, analysing bicycle traffic might need a different approach than analysing motor vehicle traffic.

The aim of this project was to get more knowledge about the manner of how gained distance-headway of cyclists influences other traffic flow characteristics of cyclists. Gained distance-headway is the distance a leader gains with respect of its follower before the follower starts moving during the queue discharge phase. It uses a data set containing the trajectory data of cyclists during the queue discharge phase at a signalized intersection on a segregated cycle path. The main goal of this research is formulated as: *The research goal is to characterize the gained distance-headway and find how it relates to macroscopic flow characteristics (discharge flow, jam density and shockwave speed).*

The insight that is attempted to be gained from this is how different spatial differences created during the green-signal phase affect other flow characteristics within the bicycle traffic flow. This gives a more fundamental insight in how individual cyclists within a queue influence the others. The conclusions of this research could be used for a better understanding of cyclists traffic and for improvement to the discharge flow.

Gained distance-headway is calculated using 2 formulas.

$$\Delta s_j = x_j(t_{j+1,1}) - x_j\,(t_0) \quad \text{if } t_{j,1} < t_{j+1,1} \tag{1}$$

$$\Delta s_j = x_{j+1}\,(t_0) - x_{j+1}(t_{j,1}) \quad \text{if } t_{j,1} > t_{j+1,1} \tag{2}$$

With Δs_j being the gained distance-headway of cyclist j, x the longitudinal position of the cyclist, t_0 being the start time of the measurements and $t_{j+1,1}$ being the time cyclist j+1 (the follower) starts moving. In the case of a cyclist starting before the green phase starts, the cyclist was not considered in the calculations, as this movement is considered an invalid movement, due to it not abiding to the traffic rules.

Calculating the gained distance-headway has been done by using both a normal lane configuration and a sub-lane configuration. A sub-lanes configuration is used to get a more accurate view of the queue. In this research, the cycle path of 2 meters wide is divided into 10 sub-lanes of 0.2 meters wide, with followers not being allowed to be more than 5 sub-lanes away from their leaders.

When comparing gained distance-headway when using a normal lane configuration between gained distance-headway when using a sub-lane configuration, it is concluded that using a sub-lane configuration gives a more accurate view of the queue.

This research found that there is a positive correlation between queue position and gained distance-headway, meaning that the gained distance-headway increases when the cyclist is further back in the queue.

This report did find a relation, but not causation, between discharge flow and the gained distance-headway with a sub-lane configuration when using a linear regression analysis. This was a negative relation, meaning that the discharge flow decreased when the gained distance-headway increased. Further research needs to be done in order to find measures to lower the gained distance-headway and how this affects the discharge flow.

Acknowledgements

This Bachelor End Project marks the end of the Bachelor phase of my studies. I would like to thank my supervisors, Dr. ir. Yufei Yuan and Dr. ir. Maria Salomons for the good support, feedback and advice they gave me during these 8 weeks. In addition, I would like to thank my fellow students Merel Sterk, Arnoud de Jong, Lizan Snoeks and Gerben van der Horst for their weekly reviews and feedback, which greatly helped me during this project.

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1. Introduction

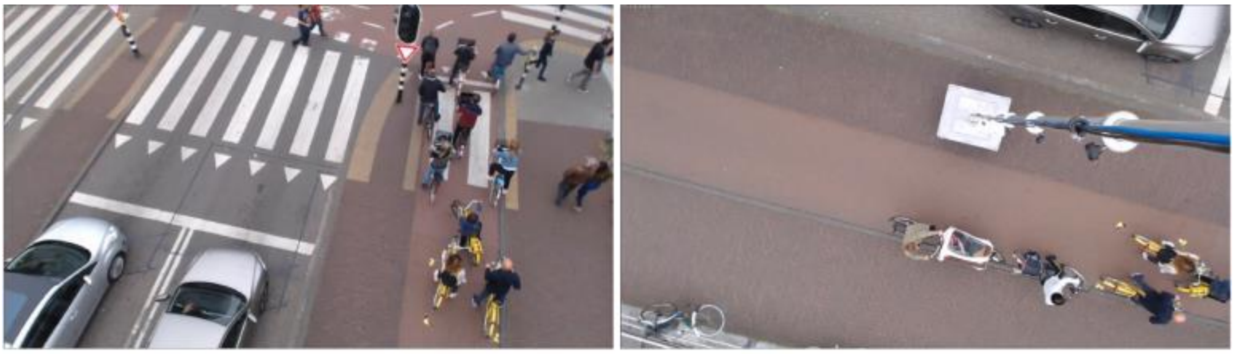
Currently, there is not much known about the flow characteristics of cyclists in bicycle lanes, especially compared to what is known about flow characteristics for motor vehicle traffic [Goñi-Ros et al., 2018]. Without the proper knowledge of these flow characteristics, bicycle traffic management has less tools to improve bicycle traffic. Given that bicycle traffic differs from motor vehicle traffic, for instance with respect to individual size and speed, analysing bicycle traffic might need a different approach than analysing motor vehicle traffic.

The project provides a data set that includes bicycle trajectory data at a stop at a signalized intersection. The goal of this project is to study bicycle traffic flow characteristics during the discharge phase of queue at a signalized intersection. This is done by using this dataset containing a microscopic flow characteristic (trajectory data) to analyse both microscopic and macroscopic flow characteristics and analyse how these different flow characteristics relate to each other.

Macroscopic flow characteristics are characteristics that describe the characteristics of the total traffic flow. The flow characteristics mentioned in this report are discharge flow, jam density and shockwave speed. Discharge flow is the amount of traffic passing the stop line per unit of time , jam density is the amount of traffic at a unit of road at standstill, which is the case before the queue discharge phase starts, and shockwave speed is the speed of a wave caused by a sudden change in the state of the traffic flow. [S. Hoogendoorn, 2012, pp. 141]

Microscopic flow characteristics are characteristics that describe an individual in the traffic flow. Examples of this are trajectories, time headways and distance headways. [S. Hoogendoorn, 2012, pp. 16]. This report focusses on the gained distance-headway, which is explained in a later section.

The data set is from Goñi-Ros et al. [2018]. It is collected at a segregated cycle path leading towards a signalized intersection on the Weteringlaan in Amsterdam. It is used by both cyclists and scooters. After crossing the stop line, the cyclists and scooters have the opportunity to turn right or to cross the intersection and turn left or go straight ahead. Figure 1 displays a satellite image of the intersection. Video footage is used to track the position of a cyclist manually, which results in the trajectory data of a cyclist, with corresponding x and y-coordinates at the corresponding time unit. The information was recorded on June 6, 2016, between 12:45 and 19:00. Before tracking, a selection of discharge periods was made, based several criteria, including having at least 7 cyclists/scooters in a discharge phase and the criteria that there is no interference by downstream traffic. More information in on how the data was collected could be found in Goñi-Ros et al. [2018]. Figure 1 displays the view of the cameras.



(a) (b)

Figure 1. Camera positions used to analyse the queue in (a) and (b) [Goñi-Ros et al., 2018] and a satellite image of the intersection at the Weteringlaan in Amsterdam [Google Earth]

This project aimed to get more knowledge about the manner of how gained distance-headway during the green-signal phase of a signalized intersection influences other traffic flow characteristics. In other words, how do the different movements in a cyclist queue during the green-signal phase influence the traffic flow characteristics. In the next section, gained distance-headway is explained and following that is an explanation of why gained distance-headway is researched, in other words, what is the meaning of the outcome of this research.

Gained distance-headway is the distance that a leader gains with respect to its follower before the follower starts moving for the first time. This is explained in figure 2.

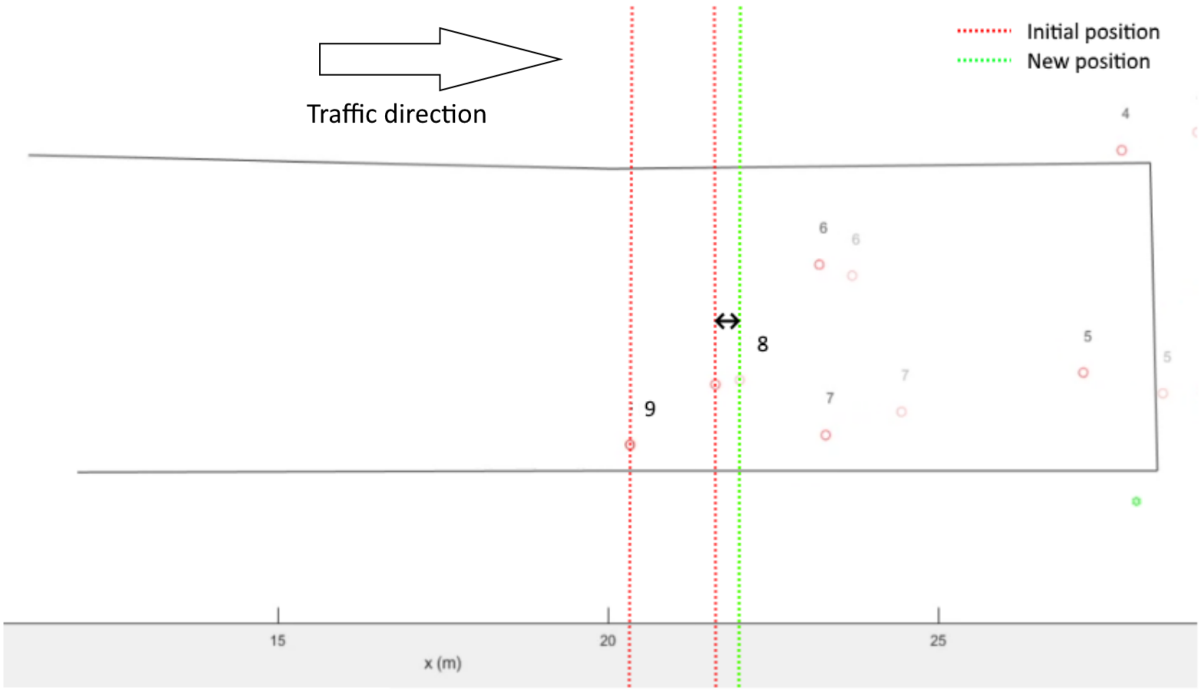


Figure 2. Gained distance headway example (x and y-axis not to scale). Data gained from Goñi-Ros et al., [2018]

With the traffic direction being to the right, this is a still from an animation made from the data set. [Goñi-Ros et al., 2018]. In this picture, 8 is defined as the leader of 9 and 9 is defined as the follower of 8. The red dotted line represents the initial positions of the respective cyclists. This is the last frame where 9 has not moved from its initial position yet. As seen here, 8 has increased its distance-headway, the distance between cyclists, with respect to 9. This new position is denoted by the green dotted line. The difference between the initial position and the new position of the leader is defined in this report as the gained distance-headway.

As an initial demarcation, the data used to analyse gained distance-headway is only be from one intersection observed during one day. This means, while the results could be generalized for similar situations, the specific results could be different when compared to other intersections. Due to time constraints, this project took place over a course of 8 weeks, the data gained from bicycle traffic is not compared to motor vehicle traffic.

The main goal that is researched during this BEP is formulated as: *The research goal is to characterize the gained distance-headway and find how it relates to macroscopic flow characteristics (discharge flow, jam density and shockwave speed).*

The main goal is analysing the microscopic flow characteristic of bicycle trajectory data and from there analyse the relation that it has with other flow characteristics. As mentioned before, gained distance-headway is a microscopic flow characteristic that measures the distance that a leader gains with respect to its follower before the follower starts moving. The gained distance-headway is a microscopic flow characteristic, since it relates to the flow characteristic of an individual cyclists instead of the total flow.

The insight that is gained from this is how different spatial differences created during the green-signal phase affect other flow characteristics within the bicycle traffic flow. This gives a more fundamental insight in how individual cyclists within a queue influence the others. This fundamental insight could be used to develop ways to increase traffic flow and lower cyclists' discomfort. Where values like reaction time measure this quantity in time [Sharma et al., 2009], this report attempts to gain insight in how differences in distance between followers and leaders influences the queue. The value of using the gained distance instead of time, as done when analysing reaction time, is that distance is a quantity that is experienced by cyclist, meaning that when in a queue, spatial differences in distance are what allow cyclists to move. It is expected that gained distance-headway has similar correlation between flow characteristics as reaction time, since a higher reaction time of the follower gives a leader more time to gain more distance. This is not discussed in this report, since the focus here is to analyse how gained distance-headway specifically influences flow characteristics.

Sub-goals are goals that help to reach the main goal of the BEP. These sub-goals are not meant as separate chapters, as is made clear later in the proposed chapter arrangement.

- *Calculate gained distance-headway*. This goal is meant as a basis for reaching the other goals. After all, without calculating the main variable used in this report, other parts will not be able to be completed. In addition, this goal is stated to give more information about this variable. The description of the calculation is discussed in the methodology part of the report, while the actual calculation and subsequent results is reported in the results part. The gained distance-headway was calculated on an individual level and the result is documented into a histogram, where the distribution of the gained distance-headway is evaluated.
- *Calculate gained distance-headway using sub-lanes*. Sub-lanes are used in order to get a more accurate picture of the influence of other cyclists on the path. While using sub-lanes, the whole path is divided into sections. How this is done is described in the methodology. The aim of this sub-goal is to get a more accurate view of the actual situation and thus, being able to determine certain relations between flow characteristics more accurately.
- *Compare the distribution of gained distance-headway using sub-lanes and normal lane configurations*. The goal here is to determine the difference in distribution of gained distance-headway when using a sub-lane method as well as using a normal lane configuration. This gives insight in how this characteristic varies between using these different methods of analysing. The difference is expressed by providing the different results of the distributions.
- *Look for a correlation between gained distance-headway and queue position, both in sub-lanes and normal.* The goal here is to see whether spatial distance from the starting line has an influence on gained distance-headway. This gives insight in how gained distance-headway is different in different sizes of waiting queues. The method of determining a correlation is by using a linear regression analysis. Linear regression is chosen to give a simple overview of the relation between the characteristics. The queue position is defined as the numerical position of the cyclist (e.g. the cyclists closest to the stop line is considered to be cyclist 1).
- *Determine the relation between the gained distance-headway and macroscopic flow characteristics discharge flow, jam density, shockwave speed using linear regression.* This sub-goal attempts to determine the between gained distance-headway and the macroscopic flow characteristics. The knowledge gained from this is to see how gained distance-headway affects these macroscopic flow characteristics. Again, linear regression is chosen to give a simple overview of the relation between the characteristics.

Chapter 2 is the Methodology, which discusses how the different aspects in this project are created and calculated. Chapter 3 contains the results of the aspects explained in the Methodology. Chapter 4 is the discussion which is followed by the conclusion in chapter 5. Chapter 6 contains the recommendations and future research topics.

2. Methodology

The methodology discusses how the different aspects in this project are created and calculated. The aspects that were created and calculated are discussed in the sub-goals stated before. It starts with an explanation about sub-lanes, followed by a brief overview of how to calculate gained distance-headway. After that, an explanation of how the gained distance-headway calculated by using sub-lanes and calculated by a normal lane configuration will be compared. It is followed by an explanation of the correlation between gained distance-headway and queue position, for both sub-lanes and a normal lane configuration. The last section will discuss how the relation between gained distance-headway and the aforementioned macroscopic flow characteristics are analysed.

2.1. Creating sub-lanes

Sub-lanes, as explained in Botma and Papendrecht [1991], are used to give a more accurate picture of the queue. As opposed to motor vehicle traffic, multiple queues can be formed within the same lane. In a normal configuration, two cyclists next to each other in the queue have a small headway in longitudinal direction, but do not experience restrain in their movements. In this case, using sub-lanes could give a more accurate view. [Botma and Papendrecht, 1991] The total lane is divided in different section called sub-lanes. Different methods of using the concept of sub-lanes are in use. For example, dividing the path up in a number of sub-lanes based on the number of separate queues that can form on the path of a specific width, as seen in Ren et al., [2015]. Another one is a virtual sub-lane, where a lane with a specific width is constructed around a specific leader, as described in Yuan et al. [2019]. Of these different methods, a fixed sub-lane method, explained in Botma and Papendrecht [1991] is chosen for this project. The reason this method is chosen is because this method gives a consistent way of using sub-lanes over different queue discharge phases.

As explained in Botma and Papendrecht [1991], using a fixed sub-lane method divides the path up in sections of a set width. It is known in which sub-lane a bicycle is situated. The cyclist in the front of the queue will be designated as a leader. The cyclist behind this leader will be designated as a follower if the cyclist is within a set number of sub-lanes from the leader, depending on the chosen width of a sub-lane. If the follower has two potential leaders within the allowed number of sub-lanes, the closest leader, in total distance, is chosen to be the leader of this follower. This process is done for the total queue. The leaders will not change during the queue discharge phase. Figure 3 gives an example.

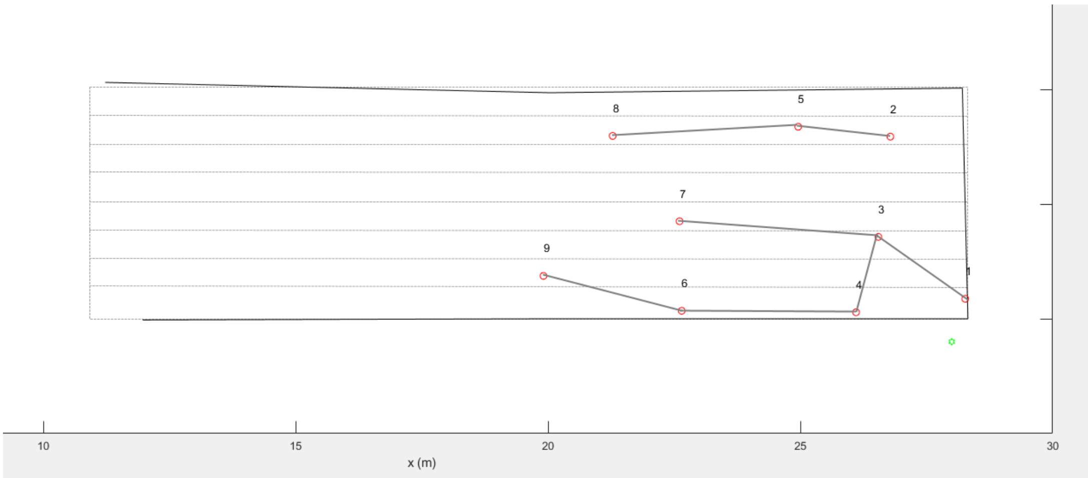


Figure 3. Example of sub-lanes as seen from above the lane. Data gained from Goñi-Ros et al., [2018]

With the direction of traffic towards the right, figure 3 displays a discharge phase present in the data set. For this example, it is chosen that the follower is allowed to be one lane away at maximum from its leader, to give an easier overview. In this picture, the numbers correspond to the predesignated order of cyclist in the queue, based on the x-position. It is clear that cyclist 1 and 2 are far apart in this situation. In this case, using sub-lanes would give a more realistic picture of the situation. Cyclist 4 will be the follower of 3, because while being in the same sub-lane of cyclist 1, cyclist 3 is closer to cyclist 4 and within the allowed number of sub-lanes. The reasoning that cyclist 4 is a follower of cyclist 3 is an assumption made in this research. In reality, it could be that cyclist 4 considers cyclist 1 as its leader. However, this can not be told from this data set, so an assumption must be made that is considered over the whole data set.

Note: while a leader can have multiple followers, a follower can only be assigned to one leader in this model.

To determine the width of the sub-lanes and number of sub-lanes, the cyclist width is needed. From literature, it is known that the design width of a cyclist is 0.75m [CROW, 2017]. Additionally, the safety distance for overtaking is stated as 0.25m [CROW, 2017]. In Botma and Papendrecht [1991], the average lateral distance between passing cyclists is stated as 1m and 0.75m, depending on how narrow the path is. In Yuan et al. [2019], it is stated that a reasonable range of sub-lane width is 1.0-1.4m, which does use a different sub-lane method, namely a virtual sub-lane method. The width of the cycle path researched here is 2m [Goñi-Ros et al., 2018].

With this knowledge, it is determined that the needed passing width is 1m, in accordance with the passing distance described before. From this, a sub-lane width needs to be determined. The width could be chosen as 1m, with the maximum sub-lane distance between cyclist being 0 sub-lanes, meaning that the cyclist needs to be within the same sub-lane. However, it could also be stated that the sub-lane width 0.2m, with the maximum sub-lane distance between cyclists being 5 sub-lanes. This will give a passing width of 5*0.2m= 1m. This will divide the total path up in 10 sub-lanes. This width is chosen over the width of 1m, due to it giving more accuracy.

2.2. Calculating gained distance-headway

As stated before, gained distance-headway is the distance-headway gained by a predisposed leader from its follower in the queue during the discharge phase up until the follower starts moving. As opposed to other methods of calculating time headway, for instance a method used in Hoogendoorn and Daamen [2016], gained-distance headway is not calculated by using a set count area, where a fixed point or line on the longitudinal x-position is chosen on which the difference in passing time is measured. Instead of the fixed point, the gained distance-headway is calculated between the starting point of leader up until the longitudinal x-position the leader reached before the follower starts moving. This makes it a combination of two instantaneous microscopic variables, namely the starting distance-headway and the ending distance-headway. [Hoogendoorn and Knoop, 2013]. It is denoted as:

$$\Delta s_j = x_j\left(t_{j+1,1}\right) - x_j\ (t_0) \tag{1}$$

With Δs_j being the gained distance-headway of cyclist j, x the longitudinal position of the cyclist, t_0 being the start time of the measurements and $t_{j+1,1}$ being the time cyclist j+1 (the follower) starts moving. In the case of a cyclist starting before the green phase starts, the cyclist was not considered in the calculations, as this movement is considered an invalid movement, due to it not abiding to the traffic rules.

This assumes that the follower will start moving after the leader starts moving. This, however, is not always the case. Therefore, another definition must be added.

$$\Delta s_j = x_j(t_{j+1,1}) - x_j\,(t_0) \quad \text{if } t_{j,1} < t_{j+1,1} \tag{1}$$

$$\Delta s_j = x_{j+1}\,(t_0) - x_{j+1}(t_{j,1}) \quad \text{if } t_{j,1} > t_{j+1,1} \tag{2}$$

If $t_{j,1} > t_{j+1,1}$ is true, that will mean that the gained distance-headway will be a negative value.

2.2.1. Total queue

For the total queue, all the gained distance-headways are calculated as explained above. In the end, all these is combined into a histogram, in which the distribution of all the gained distance-headways is visualized. This is done for both a normal lane configuration as a lane configuration using sub-lanes.

2.2.1.1. Normal lane configuration total queue

In a normal lane configuration, the order of cyclists is predetermined by the position from the start line (longitudinal x-value) at the start of the green phase [Goñi-Ros et al., 2018]. This is the order used to calculate the gained distance-headways. The results of all gained distance-headways are displayed in a histogram.

2.2.1.2. Sub-lanes total queue

Sub-lanes are implemented and used to calculate the gained distance-headway as described in section 2.1. This gives the determination of follower and leader, leading to a different distribution of gained distance-headway.

2.2.2. Per position in queue

A sub-goal, as discussed in the introduction, is to look for a correlation between gained distance-headway and queue position. The correlation is explained later, but in this section, the gained distance-headway is calculated per position. The result is displayed in several histograms denoting the distribution of the gained distance headway per position in the queue.

2.2.2.1. Normal lane configuration per position

For the normal lane configuration with the predetermined order of cyclists, the gained distance-headway is calculated as explained, with the position in the queue determined by the position given at the start of the measurements, as denoted in [Goñi-Ros et al., 2018].

2.2.2.2. Sub-lanes per position

By using sub-lanes, the total number of individuals in a queue could get lower than when using a normal lane configuration, as the total queue gets divided into different queues. For example, a total queue of 10 cyclists could get divided into 2 queues of 5 cyclists. This gives less graphs as a product, as there are less positions within those queues, but more data within those graphs, as the same number of individual cyclists are counted.

2.3. Comparing normal lane configuration and sub-lanes

The goal of comparing the gained distance-headway calculated by using the normal lane configuration with the configuration using sub-lanes is to see the differences between the two configurations. Doing this gives an insight in which lane configuration gives a more accurate view of the actual situation.

The distribution of the value of gained distance-headway is displayed in a histogram. From this, the median value and standard deviation can be retrieved, while also giving the value of the 0.25 and

0.75 quantiles. This gives an insight in the differences between a normal lane configuration and a sub-lane configuration.

2.4. Calculating correlation between queue position and gained distance-headway

This is also done while considering the position in the queue, both while using a normal lane configuration and sub-lane configuration. The queue position with the normal lane configuration is predetermined and the queue position. From this, the distributions for different positions in the queue are determined. This is displayed in multiple histograms, for each position one.

It could be the case that at the maximum value of queue position, not enough of data is available, since it does not happen very often that the queue reaches that specific length. Thus, a cut-off of position to analyse was made, based on the amount of data available. This was done by cutting off the data when a certain number of cyclists is counted, in this case 90%.

The same thing as before is done here, by noting and comparing the median value and standard deviation of each. In addition, a linear regression analysis between the median value and queue position and the standard deviation and queue position was performed, in order to see how they relate. This is denoted as:

$$y = \alpha + \beta * x \quad (3)$$

With y being the median value or the standard deviation, x the queue position, α the intercept and β the slope. The intercept and the slope were calculated using MATLAB.

2.5. Calculating relation gained distance-headway and macroscopic flow characteristics

In this section, the method for calculating the relation of the gained distance-headway and macroscopic flow characteristics is explained. As mentioned before, these macroscopic flow characteristics are jam density, shockwave speed and discharge flow. These macroscopic flow characteristics were calculated per discharge phase before this project started. [Goñi-Ros et al., 2018]. A short explanation of the macroscopic flow characteristics can be found in the introduction.

The jam density was calculated by dividing the number of cyclists minus one by the distance of the cyclist farthest from the stop line to the stop line minus the distance of the cyclists closest to the stop line from the stop line at standstill. This is displayed by L in figure 4. This is then standardized by dividing it by the cycle path width.

Shockwave speed per queue was calculated by fitting a line using linear regression in the trajectory plot through the locations before the cyclist j =1,….,N starts moving. The intercept is fixed at the position before cyclist 1 starts moving. The slope of the fitted line is defined as the shockwave speed of the queue. The line is shown in figure 4.

Discharge flow was calculated by creating a count area after the stop line. The longitudinal distance of this count area is noted as Δx. The time between the first cyclist reaching the end of the count area and the last cyclists reaching the end of the count area is noted as well, denoted as Δt. In this time, the distance all the cyclists (minus the first) in the queue travel within this count area is measured. This value is divided by Δx, Δt and the width of the lane. In figure 4, the count area is shown in green, with Δx and Δt displayed as well. The trajectories of the cyclists are the grey lines. As it only shows the x-position (longitudinal position) of the cyclist, it is possible for the lines to cross, displaying a cyclist being overtaken at that x-position.

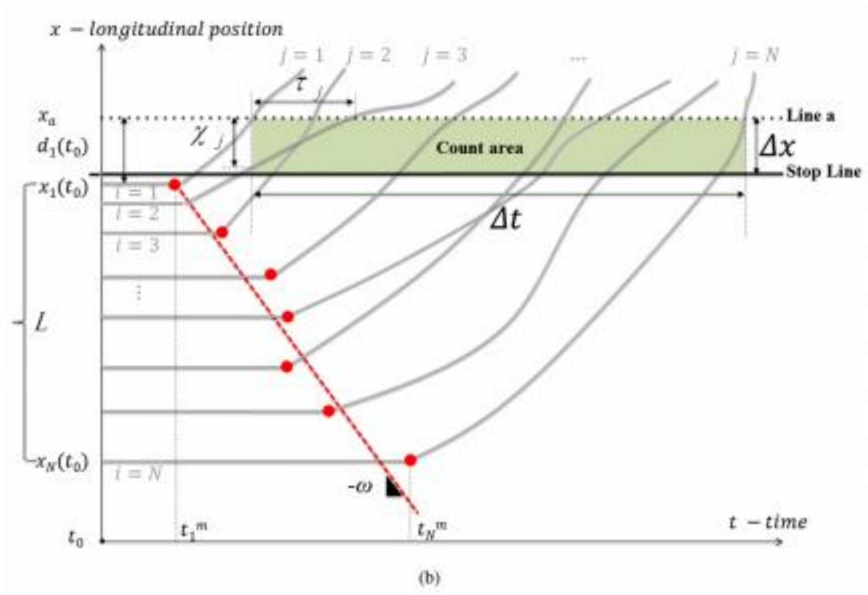


Figure 4. Calculation of the macroscopic flow characteristics. Goñi-Ros et al., [2018]

The problem arising here is the transition from the microscopic flow characteristic describing an individual cyclist to the macroscopic flow characteristic describing a total queue. In order to do this, the value of the individuals in a queue must be changed into a value representative of the total queue. This was done by taking the median value of the gained distance-headway by all the cyclists within the queue. The median value is chosen instead of the mean, as this is less influenced by the extreme values within the data set, making it a more representative value for the expected value. This value is considered as representative for the total queue.

As mentioned in section 2.3, a normal lane configuration will be compared to a sub-lane configuration. These configurations, after all, have different ways to assign a leader and follower and thus different values in gained distance-headway per queue. While in section 2.3, the gained distance-headway was compared between the methods, this section will calculate the relation between the median gained distance-headway per queue and the macroscopic flow characteristics mentioned before. Thus, this section does not directly focus on how the lane configurations are different, but rather display the different results gained by using different lane configurations. The median value of calculated gained distance-headways while using sub-lanes is still considered to be representative of the total queue, since sub-lanes are used to assign leaders and corresponding followers, thus not resulting in different cyclists being in the same queue discharge phase.

With the corresponding macroscopic flow characteristic and median gained distance-headway known for each queue discharge phase, a linear regression analysis is performed, for both sub-lanes and normal lane configuration. These values are displayed in a scatterplot. After this, a linear equation is stated as:

$$y = \alpha + \beta * x \quad (3)$$

With y being the corresponding macroscopic flow characteristic, x the median gained distance headway, α the intercept and β the slope. The intercept and the slope were calculated using MATLAB. Linear regression is used in order to simple overview of the relation between the gained distance-headway and the macroscopic flow characteristics.

To see how the linear regression performed, F-tests and t-tests was performed, with a desired significance of 5%. This significance is chosen arbitrarily, but as, a rule of thumb is that at a p-value higher than 0.05, reasonable doubt begins. [Dekking et al. , 2005]

3. Results

In this chapter, the results will be discussed. In section 3.1, the calculated gained headway-distance will be displayed, for both a normal lane configuration as a sub-lane configuration. In section 3.2, these results will be discussed. In section 3.3, the gained distance-headway per queue position will be discussed. In section 3.4, the correlation between queue position and gained distance-headway will be calculated. In section 3.5, the relation between gained distance-headway and the macroscopic flow characteristics will be analysed.

3.1. Gained distance-headway

The gained distance-headway per lane configuration (normal and sub-lanes), is calculated as described before. The results are displayed in table 1, with the abbreviation GDH used for gained distance-headway. The corresponding graphs displaying the distributions are in figure 5.

Table 1 Gained distance-headway per lane configuration

	Normal lane configuration	**Sub-lane configuration**
Amount of observations	634	528
Mean GDH	0.19 m	0.21 m
Median GDH	0.07 m	0.14 m
0.25 percentile	-0.08 m	0.00 m
0.75 percentile	0.36 m	0.39 m
Standard deviation	1.03 m	0.60 m
Maximum value GDH	7.50 m	4.44 m
Minimum value GDH	-6.95 m	-3.63 m
Amount of positive values	420 (66.2%)	410 (77.7%)
Amount of negative values	214 (33.8%)	118 (22.3%)

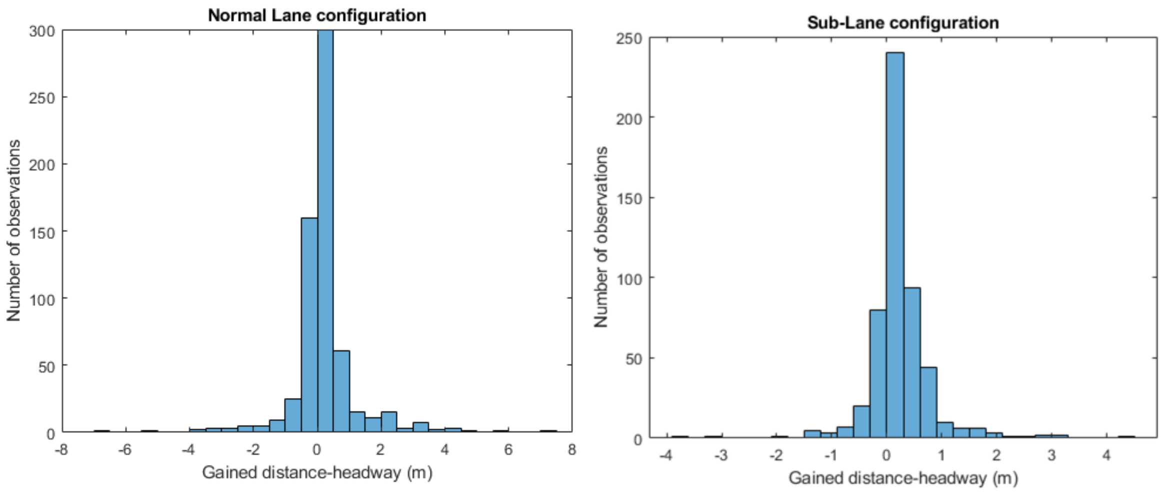


Figure 5 Gained distance-headway distributions for both lane configurations

3.2. Comparing results normal lane configuration and sub-lanes

The amount of observations is lower when using sub-lanes, since using a sub-lane configuration results in more lanes, which have more cyclists that do not have a follower, e.g. the last cyclist of the queue.

The standard deviation when using a sub-lane configuration is lower than when using a normal lane configuration, which means the data is closer to the mean when using a sub-lane configuration. This could mean that using sub-lanes gives a more accurate view of the actual situation, since there is less variance within the data set. Less variance in the data means that there is more data around the expected value. When looking at the graphs, most values fall around the corresponding medians for both lane configurations, so this is an aspect that is expected for gained distance-headway. If this aspect is expected, a lower standard deviation suggests a more expected or accurate view of the actual situation.

The mean and median while using sub-lanes is higher, which could mean that it gives a more accurate view of the dynamics in a queue. As mentioned in section 2.1, a reason why sub-lanes could be beneficial to use is that it gives a more accurate view of which followers experience restrain in their movements because of their leaders. A higher value of gained distance-headway means that the leader gained more distance with respect to its follower, or in other words, that the follower had to allow the leader more distance in order to move themselves. Especially with the aforementioned lower standard deviation, it suggests that this is what is usually happening in a queue, since a lower variance shows that more values are around the expected value.

The maximum and minimum value of gained distance-headway are closer to the mean when using sub-lanes, which could mean, together with the lower standard deviation, that using sub-lanes gives a more accurate view. These extreme values could be the result of a scooter or an e-bike in the queue, since they accelerate faster than a normal cyclist. As mentioned in section 2.2, a negative value means that the follower started moving before the leader.

Lastly, the percentage of positive values is higher when using sub-lanes. This means that there are less instances of followers starting before leaders when using sub-lanes. This also suggests that using a sub-lane configuration gives a more accurate view of the dynamics in a queue. A standard way of discharge is that the follower starts after the leader, as there needs to be space in front of a follower to move, thus the standard way of discharge gives more positive gained distance-headways.

This all, however, is analysis of the accuracy based on some values of the distribution. Which lane configuration gives the best description of the actual situation can only be determined with a more extended analysis at a microscopic level, where the chose of leader of each individual cyclist is determined. This is beyond the scope of this research, so this method is chosen instead.

3.3. Queue position

In this section, the gained distance-headway per queue position will be displayed. As mentioned in section 2.2.2, the amount of positions while using sub-lanes is lower. As seen in section 3.1, the amount of observations is lower when using sub-lanes, which is also reflected in these results.

When using a normal lane configuration, the maximum length of a queue is 20 cyclists. Cut of point is when the amount of cyclist counted has reached 90%, meaning that the 10% of all the cyclists in the last positions were counted.

With 90% of the cyclists, the maximum position is 12 when using a normal lane configuration. The characteristics are displayed in table 2. Count is the number of cyclists at the corresponding position, the other columns display the median value, mean value and standard deviation of gained distance-headway per position. The corresponding graphs can be found in Appendix A.

Table 2. Characteristics of gained distance-headway per position for a normal lane configuration

Position	Count	Median [m]	Mean [m]	Standard deviation [m]
1	52	0.00	-0.01	0.54
2	56	0.05	0.04	0.98
3	58	0.00	-0.14	1.25
4	59	0.17	0.43	1.33
5	58	0.04	0.29	1.23
6	56	0.16	0.41	1.09
7	56	0.08	0.10	0.89
8	54	0.14	0.28	0.69
9	47	0.13	0.24	1.02
10	41	0.06	0.28	0.90
11	28	0.10	-0.04	0.84
12	25	0.16	0.38	0.82

When using a sub-lane configuration, the maximum length of a queue is 11 cyclists. Cut of point here is when the amount of cyclist counted has reached 90% as well. With 90% of the cyclists, the maximum position is 7 when using a sub-lane configuration. The characteristics are displayed in table 3.

Table 3.Characteristics of gained distance-headway per position for a sub-lane configuration

Position	Count	Median [m]	Mean [m]	Standard deviation [m]
1	81	0.11	0.12	0.45
2	89	0.12	0.16	0.68
3	91	0.12	0.31	0.75
4	80	0.16	0.23	0.46
5	65	0.18	0.21	0.41
6	46	0.20	0.26	0.74
7	32	0.20	0.39	0.73

The corresponding graphs are found in Appendix B.

3.4. Correlation between queue position and gained distance-headway

In order to see if there is a correlation between the queue position and the gained distance-headway, a linear regression was used. This was done for both a normal lane configuration as well as a sub-lane configuration. As mentioned in section 3.3, the first 90% of cyclists are considered significant and were used in the linear regression. Per lane configuration, two linear regression were performed, one on the median value per queue position and one on the standard deviation per queue position. The t-test and F-test were performed by testing the variables with the null hypothesis of $H=0$ against the hypothesis of $H\neq0$. In other words, the null hypothesis is that there is no relation between the median gained distance-headway per queue and queue position or between the standard deviation of gained distance-headways per queue and queue position. The t-test and F-test are statistical tests used in order to test the fit of the linear regression.

3.4.1. Median

The median value per queue position is calculated and by looking at the regression, it could be shown how the gained distance-headway of cyclists changes for the queue position. The results are displayed in table 4.

Table 4. Linear regression statistics for the median value per queue position

Median	F-stat	p-value	R^2	Estimate	SE	t-stat	p-value
Normal lanes	4.2732	0.0656	0.2994				
α				0.0302	0.0334	0.9060	0.3863
β				0.0094	0.0045	2.0672	0.0656
Sub-lanes	59.1	0.0006	0.922				
α				0.084	0.010	8.314	0.001
β				0.017	0.002	7.688	0.001

In table 4, the Estimate column gives the estimated value of α and β in equation (3) based on the linear regression done. The column SE gives the standard error of α and β based on the linear regression.

For normal lanes, the R^2-value is 0.299, which means that the queue position counts for 29.9% of the variance of the median gained distance-headway. The p-value of the F-statistic is 0.0656, which is not a desired value for the significance condition that $p<0.05$. In addition, the p-value of the t-stat of β is not lower than 0.05, which suggests that the estimate of 0.0094 is not correct. This means that when using normal lanes, a linear regression does not give a significant relation between queue position and gained distance headway.

For sub-lanes, the queue position counts for 92.2% of the variance of the median. The p-value of the F-statistic is lower than 0.05. The p-values for both α and β are lower than 0.05 as well. This means that the calculated fit is a correct one to use. Equation (3) could be rewritten as:

$$y = 0.084 + 0.017 * x \quad (4)$$

For both a normal lane configuration and a sub-lane configuration, gained distance-headway and queue position are positively related. Graphs for the median value per queue position are displayed in figure 6. The specific values can be found in table 2 and table 3 in section 3.3.

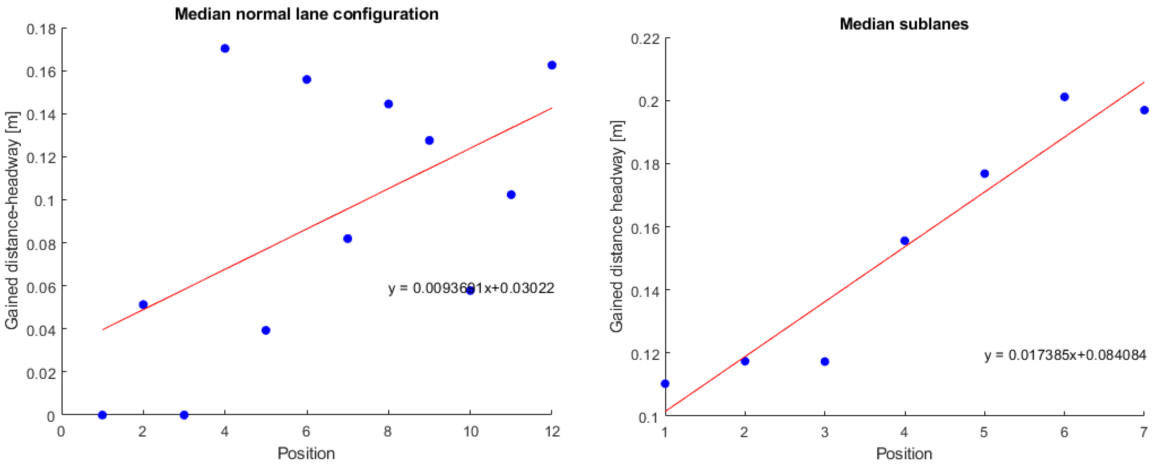


Figure 6 Median value per lane position for both lane configurations

3.4.2. Standard deviation

By looking at the regression of the standard deviation, it could be shown whether the values of gained distance-headway vary a lot when looking at the queue position. In other words, whether the gained distance-headway of the cyclists in the front is easier to predict than the gained distance-headway of cyclists further down the queue. The results are displayed in table 5.

Table 5. Linear regression statistics for the standard deviation per queue position

Standard deviation	F-stat	p-value	R^2	Estimate	SE	t-stat	p-value
Normal lanes	0.4836	0.5026	0.046				
α				1.054	0.148	7.133	3.17e-05
β				-0.014	0.020	-0.695	0.503
Sub-lanes	0.0596	0.817	0.0118				
α				0.508	0.136	3.748	0.013
β				0.023	0.030	0.768	0.477

For both a normal lane configuration and a sub-lane configuration, the p-value for F-stat are much bigger than 0.05. The same counts for the p-value of β. The value for α is for both lane configurations lower than 0.05. However, due to the high p-value of both F-stats, the null hypothesis of α=0 and β=0 can not be rejected, meaning that the standard deviation is not related to queue position, for both lane configurations. Figure 7 displays the graphs showing the linear regression of the standard deviation per queue position for both lane configurations.

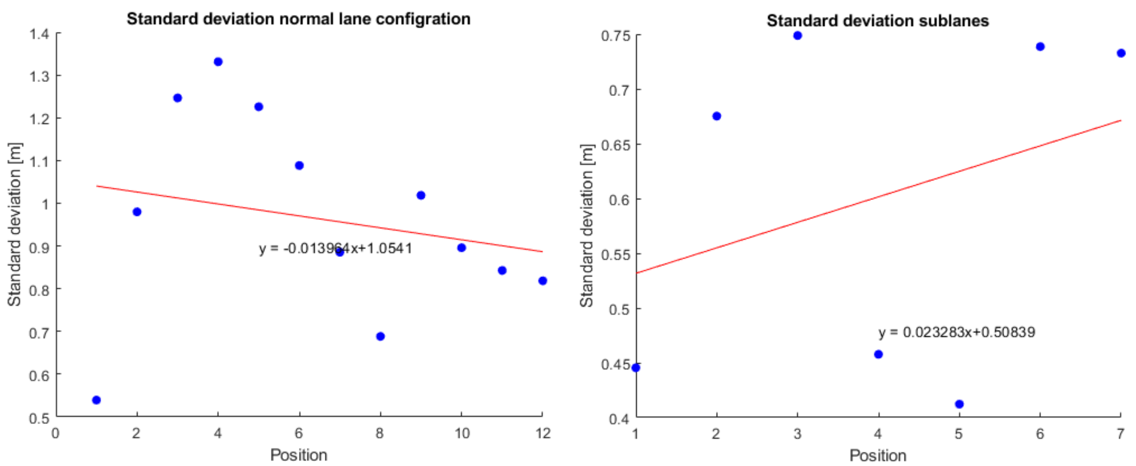


Figure 7 Standard deviation of gained distance-headway per queue position for both lane configurations

3.5. Relation between gained distance-headway and macroscopic flow characteristics

In this section, the relation between gained distance-headway and the macroscopic flow characteristics jam density, shockwave speed and discharge flow are calculated. As mentioned in the introduction, this is done by a linear regression analysis. The null hypothesis is set at H=0 and is tested against the hypothesis of H ≠ 0.

3.5.1. Jam density

This section contains the analysis of the linear regression for jam density. Table 6 displays the characteristics of the linear regression and figure 8 displays graphs displaying the linear regression for both lane configurations.

Table 6. Linear regression statistics for the jam density and gained distance-headway

	F-stat	p-value	R^2	Estimate	SE	t-stat	p-value
Normal lanes	0.5171	0.4750	0.090				
α				0.455	0.012	39.73	3.05e-43
β				-0.005	0.019	-0.7191	0.4750
Sub-lanes	2.080	0.1547	0.0352				
α				0.470	0.016	29.005	8.05e-36
β				-0.135	0.094	-1.442	0.155

For both lane configurations, the value of R^2 is low (<0.1), meaning that the variance of the data is not explained by the gained distance-headway. In addition, for both lane configurations, the p-value of the F-stat is higher than 0.05. However, when using a normal lane configuration, it is much higher than when using a sub-lane configuration. Both methods can not reject the null hypothesis, but the sub-lane configuration performed a better linear regression than the normal lane configuration.

From this, it is concluded that there is no relation between the gained distance-headway and the jam density when using a normal lane configuration. When using a sub-lane configuration however, there is a higher chance of a negative relation between gained distance-headway and jam density. However, it does not meet the desired significance level, meaning it will not be concluded here.

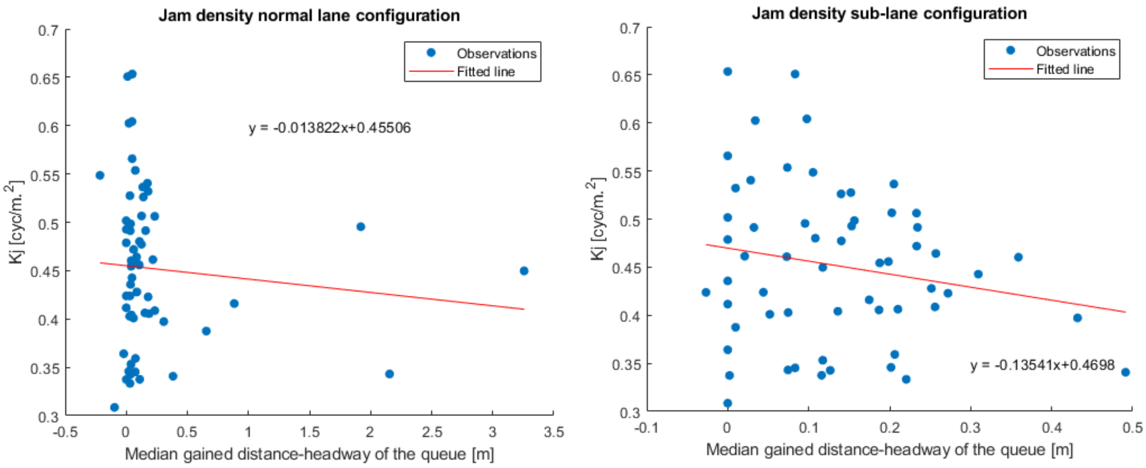


Figure 8 Linear regression jam density and gained distance-headway for both lane configurations

3.5.2. Shockwave speed

This section contains the analysis of the linear regression for the shockwave speed. Table 7 displays the characteristics of the linear regression and figure 9 displays graphs showing the linear regression for both lane configurations.

Table 7. Linear regression statistics for shockwave speed and gained distance-headway

	F-stat	p-value	R^2	Estimate	SE	t-stat	p-value
Normal lanes	0.51379	0.4764	0.009				
α				4.091	0.364	11.240	4.36e-15
B				-0.438	0.611	-0.717	0.4764
Sub-lanes	0.673	0.416	0.012				
α				4.319	0.521	8.293	2.25e-11
β				-2.476	3.019	-0.820	0.416

For both lane configurations, the p-value of the F-stat is much higher than the desired 0.05. In addition, the p-value for the t-statistic of β is much higher than 0.05. The values of R^2 are very low as well.

From this, it is concluded that there is no linear relation between shockwave speed and gained distance-headway.

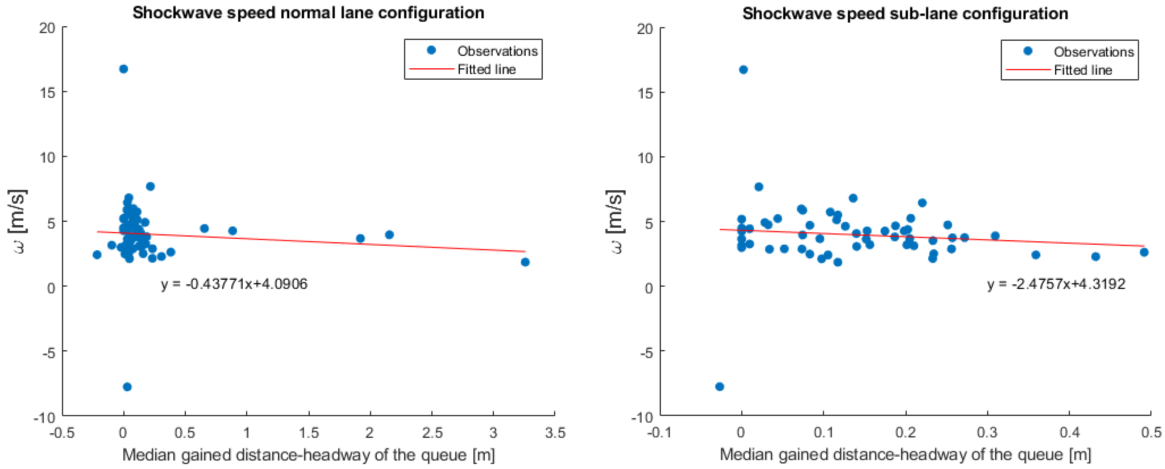


Figure 9 Linear regression of shockwave speed and gained distance-headway for both lane configurations

3.5.3. Discharge flow

This section contains the analysis of the linear regression for the discharge flow. Table 8 displays the characteristics of the linear regression and figure 10 displays graphs showing the linear regression for both lane configurations.

Table 8. Linear regression statistics for the discharge flow and gained distance-headway

	F-stat	p-value	R^2	Estimate	SE	t-stat	p-value
Normal lanes	3.15	0.08	0.052				
α				0.615	0.014	44.20	8.435 e-44
β				-0.042	0.023	-1.776	0.0811
Sub-lanes	4.138	0.047	0.01				
α				0.637	0.020	32.178	3.03e-38
β				-0.233	0.115	-2.034	0.047

For a normal lane configuration, the p-value of both the F-stat and β are higher than 0.05. This, together with the low value of R^2, results in there not being a linear relation between discharge flow and gained distance-headway when using a normal lane configuration.

When using a sub-lane configuration, the p-value of the F-stat is lower than 0.05. In addition, the p value of the t-stat of α and β is lower than 0.05. This suggests a linear relation between discharge flow and gained distance-headway when using a sub-lane configuration. It must be noted that the value of R^2 is low (R^2=0.01). This means that 1% of the variance of the discharge flow could be explained by the median gained distance-headway of the queue. This means that while there is a linear relation between the gained distance-headway and discharge flow while using sub-lanes, the value of the median gained-distance headway of the queue does not explain the value of the discharge flow of the queue. Thus, while there is a linear correlation between the values, it does not imply causation. Nevertheless, the linear correlation could be written as:

$$y = 0.637 - 0.233 * x \tag{5}$$

In this linear formula, it is seen that there is a negative relation between gained distance-headway and discharge flow when using sub-lanes, meaning that a higher value of gained distance-headway relates to a lower value of discharge flow.

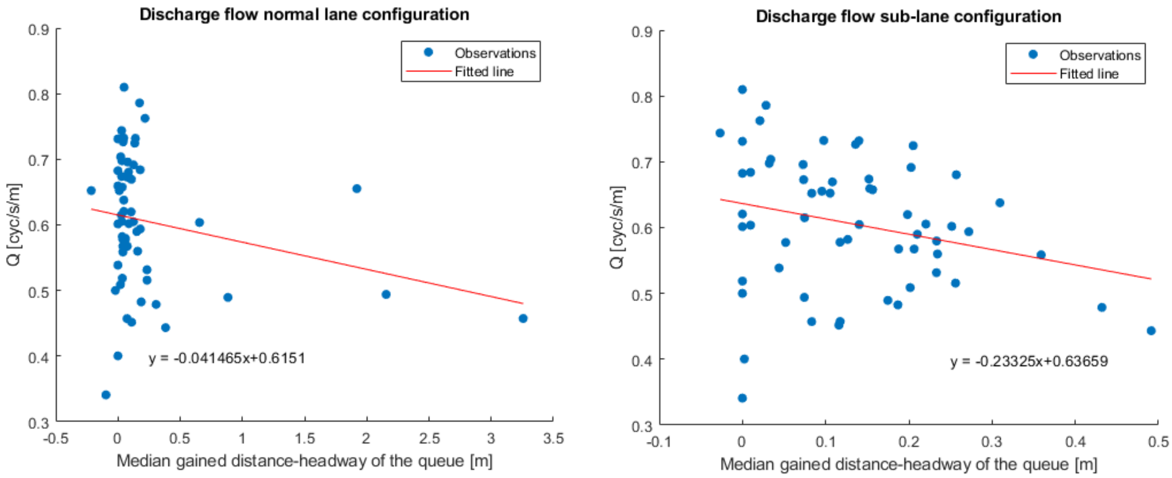


Figure 10 Linear regression of discharge flow and gained distance-headway for both lane configurations

4. Discussion

In this research, the method of using fixed sub-lanes is chosen. This usually gave a better fit than using a normal lane configuration when finding a relation between the gained distance-headway and the macroscopic flow characteristics. A different method of using sub-lanes might give a more accurate view of the actual situation.

When researching a relation between the gained distance-headway and the macroscopic flow characteristics, a linear regression was used. This did not result in a significant relation between the gained distance-headway and most of the flow characteristics, except the discharge flow when using sub-lanes. Other regression methods could be used, such as an exponential regression. In addition, other types of linear regression, such as a multiple linear regression could be used in future research. In addition, the desired p-value of 0.05 could also be increased.

There could be a discussion about the future usability of the dataset as well. This, however, does not impair the methodology and research done here, but rather, it might give different results when doing the measurements today.

The data here is specifically from a cycle path at a signalized intersection in Amsterdam containing both cyclists and scooters. After crossing the stop line, the cyclists and scooters can turn right, or cross the intersection and turn left or go straight ahead. This methodology of calculating gained distance-headway could be used for queue discharges at other intersections as well, but it might result in different results. Cyclists might accelerate more if they do not have to make a right turn right after the stop line or the amount of traffic making a right turn is different. In addition, other types of queue discharges might give different results, for example, a queue discharge after a bridge closing or a railway level crossing. These situations could give other dynamics, such as more cyclists starting before the green light phase starts. In addition, a wider cycle path gives more space to overtake cyclists in front, which could result in more negative values. This is already seen in the difference between a normal lane configuration and a sub-lane configuration, where sub-lanes are in effect a narrower cycle lane. This, however, could be a topic of future research.

The dataset is from 2016. Between now (2020) and 2016, some aspects with regards to cycling and cycle paths changed. Firstly, the number of e-bikes sold in The Netherlands has increased, from 29% of all new bicycle sales in 2016, to 42% in 2019. E-bikes can accelerate faster than normal bicycles, which could result in a different gained distance-headway. [RAI Vereniging, 2020] This could be a topic for future research.

In addition, in the data from 2016, scooters were included. In 2019, scooters were banned from the cycle path within the city centre of Amsterdam. This also includes the street where the measurements were taken (Weteringlaan). Similar to the increase in e-bikes, a different configuration of types of traffic on a path could influence the gained distance-headway.

Lastly, at the time of writing this report, the world and The Netherlands is experiencing a pandemic due to COVID-19. Dutch government guidelines recommend keeping a distance of 1.5 meters between people in order to minimize the risk of infection. This report focusses on distance between individuals, analysing it based on data from 2016. It is possible that the attitude towards distancing between individuals changes in the future. This could be an interesting topic of further research for after the COVID-19 pandemic.

5. Conclusion

The main goal that researched during this BEP was formulated as: *The research goal is to characterize the gained distance-headway and find how it relates to macroscopic flow characteristics (discharge flow, jam density and shockwave speed).* In addition, multiple sub-goals were stated in the introduction.

Using sub-lanes gives a more accurate view of the actual situation and the dynamics of followers with respect to their leaders. This is concluded by the lower standard deviation, the higher mean and median value and the higher percentage of positive values of gained distance-headway.

Gained distance-headway has a positive linear relation with the queue position when using a sub-lane configuration. When using a sub-lane configuration, the relation is described by:

$$y = 0.084 + 0.017 * x \quad (4)$$

With y being the gained distance-headway and x the position in the queue. This observation means that leaders get more distance with respect to their followers before the followers start moving when they are further along the queue. This is possibly because of the increased spatial differences in the queue the further along the queue discharge phase is. Formulated differently, if the cyclists before the leader already started moving, more space is created for the leader to move into, which in turn means that they could get more distance from their follower.

There was no relation found between the standard deviation of gained distance-headway per queue position and queue position. This, together with the low R^2 values found in the analysis between gained distance-headway and macroscopic flow characteristics, displays the stochastic nature of cyclist traffic.

The only linear relation between gained distance-headway and the macroscopic flow characteristics found was with discharge flow while using a sub-lane configuration. However, the value of R^2 is low, meaning there is no causation between the two values. The linear relation is written as:

$$y = 0.637 - 0.233 * x \quad (5)$$

In this linear formula, it is seen that there is a negative relation between gained distance-headway and discharge flow when using sub-lanes, meaning that a higher value of gained distance-headway relates to a lower value of discharge flow. This means that when the spatial differences when starting up increase, the rate at which the cyclists cross the stop line per unit of time decreases. This could logically be explained by the fact there is more distance between cyclists. However, with the low value of R^2, it is suggested that there are more important factors to discharge flow than gained distance-headway.

Other macroscopic flow characteristics did not show a relation with gained distance-headway when using a linear regression analysis.

6. Recommendations and future research

From this research, it is concluded that gained distance-headway is negatively linearly related with discharge flow when using a sub-lane configuration. While not giving a causation, a lower discharge flow is related to a higher gained distance-headway. Measures to reduce gained distance-headway could have a positive impact on the discharge flow. These measures and their effectiveness could be a topic of future research.

These measures could include measures that make cyclists start faster, such as countdown timers. Further research could be done on these measures, with a focus on how it affects gained distance-headway and the macroscopic flow characteristics.

In addition, a different method of calculating sub-lanes could be used, for instance a virtual sub-lane method. This could result in a different configuration of leaders and followers, which could affect the results.

A different regression could be used in order to analyse the relation between gained distance-headway and the macroscopic flow characteristics. Linear regression was chosen in this research to give a simple overview of the relation between the variables.

A different significance level than 0.05 could be applied, which alters the conclusions. Especially combined with another future research topic, this change could show different results and conclusions.

In addition, another type of signalized intersection could be used, for instance a level crossing of a railroad. This research was only limited to a single type of signalized intersection. Another cycle path with a different width than 2 meters or a two directional cycle path might also give different results.

Lastly, further research could be done with a new data set, noting the changes in bicycle traffic that happened in the last years, as discussed in the discussion.

Bibliography

H. Botma and H. Papendrecht. *Traffic operation of bicycle traffic*. Transportation Research Record, (1320), 1991.

CROW. Bicycle dimensions. *Design manual for bicycle traffic*. CROW, 2017

F.M. Dekking, C. Kraaikamp, H.P. Lopuhaä and L.E. Meester. *A Modern Introduction to Probability and Statistics. Understanding Why and How,* page 379. Delft. Springer, 2005.

S. Hoogendoorn. *CT4821: Traffic Flow Theory and Simulation*. TU Delft. 2012.

S. Hoogendoorn and W. Daamen. *Bicycle Headway Modeling and Its Applications*. Transportation Research Record, (1320), 2016.

S. Hoogendoorn and V. Knoop. Traffic flow theory and modelling. *The Transport System and Transport Policy: An Introduction*, pages 125–159, 2013.

B. Goñi -Ros, Y. Yuan, W. Daamen, and S. Hoogendoorn,. *Empirical analysis of the macroscopic characteristics of bicycle flow during the queue discharge process at a signalized intersection*. Transportation Research Record, (2672), 2018.

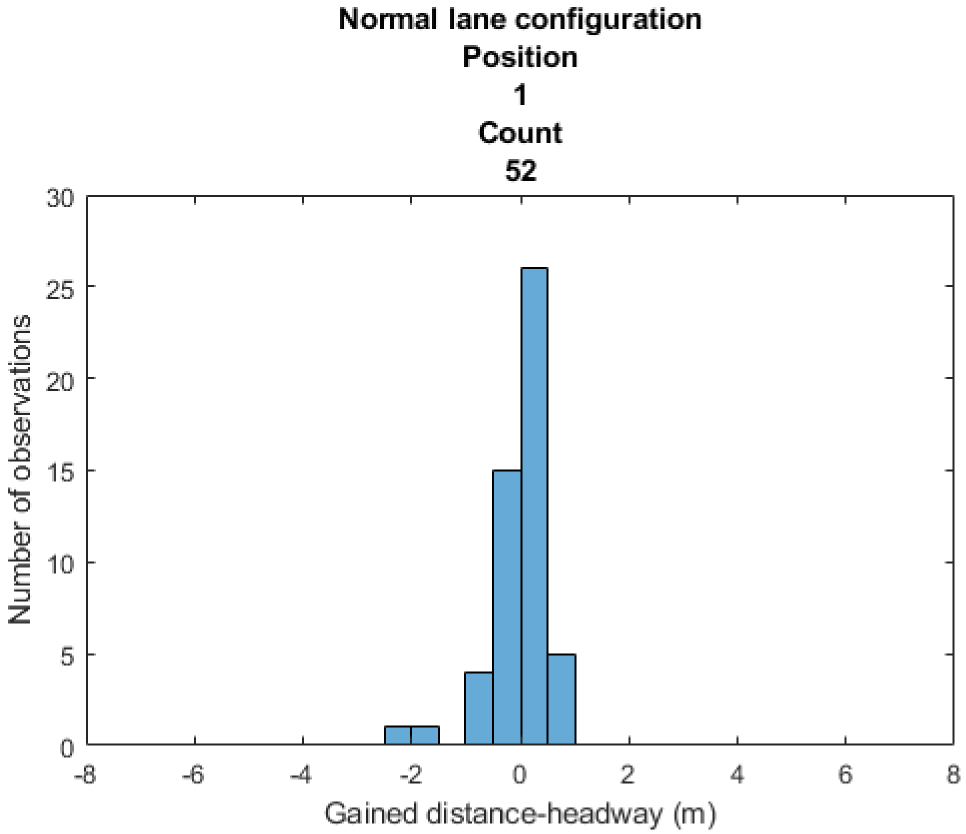
RAI Vereniging, *Verkoopcijfers Fietsen 2007-2019*. 2020

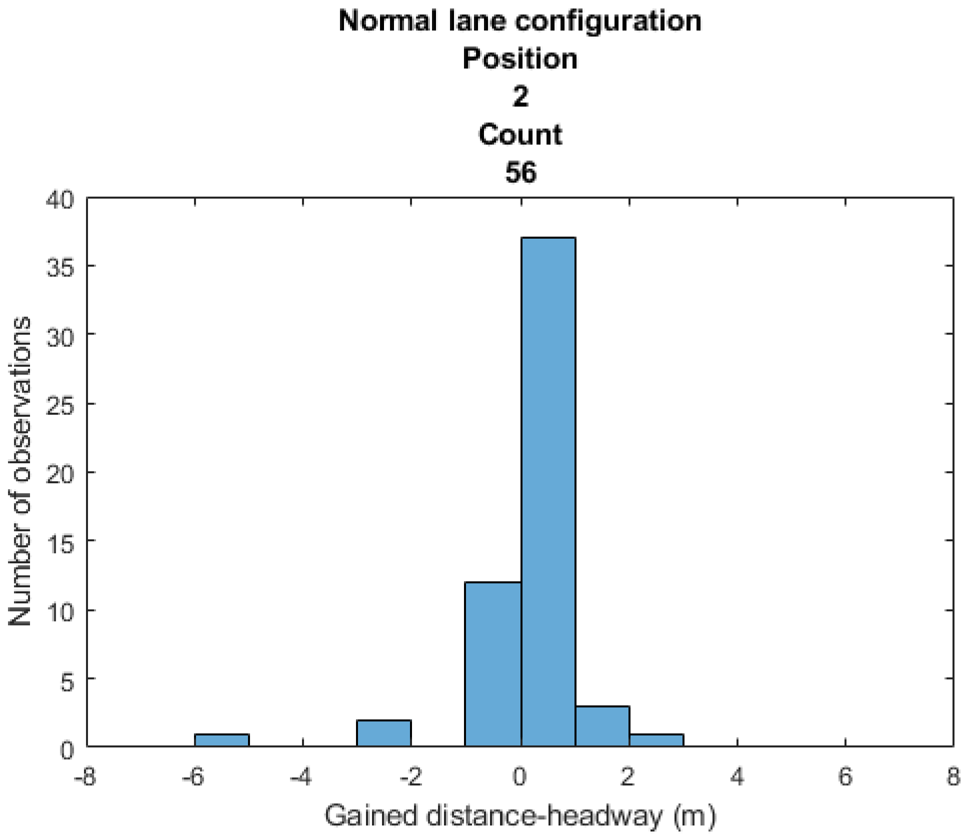
G. Ren, H. Jiang, J. Chen, Z. Huang, L. Lu. *Heterogeneous cellular automata model for straight-through bicycle traffic at signalized intersection.* Physica A: Statistical Mechanics and its Applications, (451). 2016

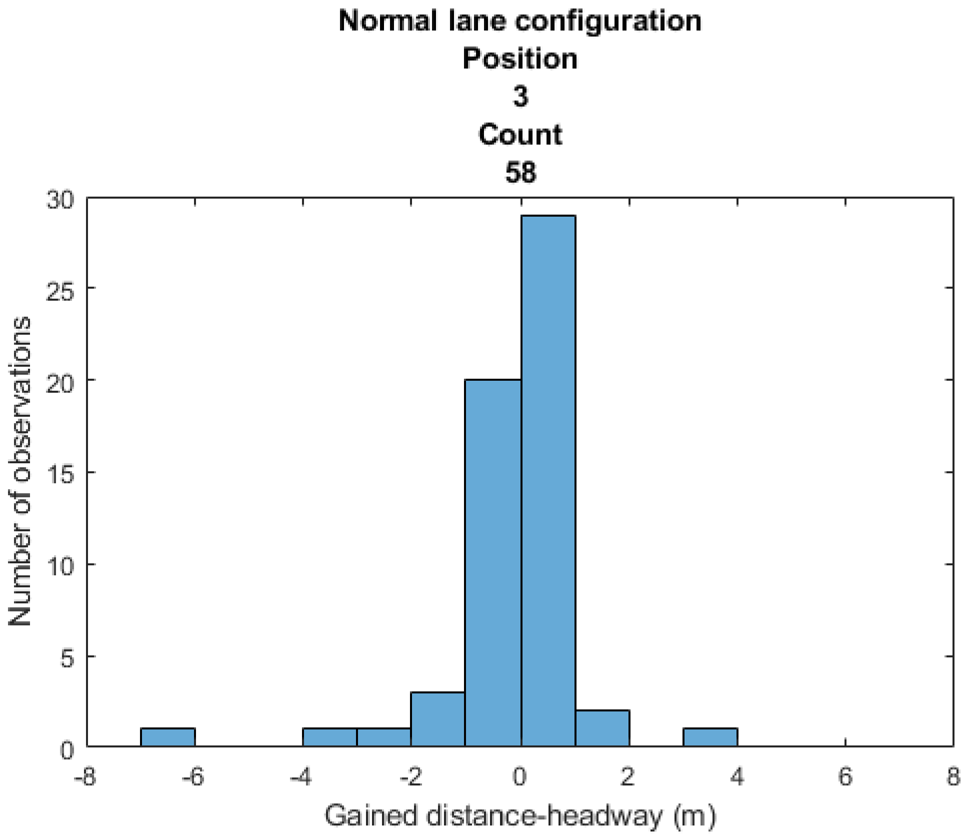
A. Sharma, L. Vanajakshi, N. Rao. *Effect of Phase Countdown Timers on Queue Discharge Characteristics Under Heterogeneous Traffic Conditions.* Transportation Research Record, (2130), 2009.

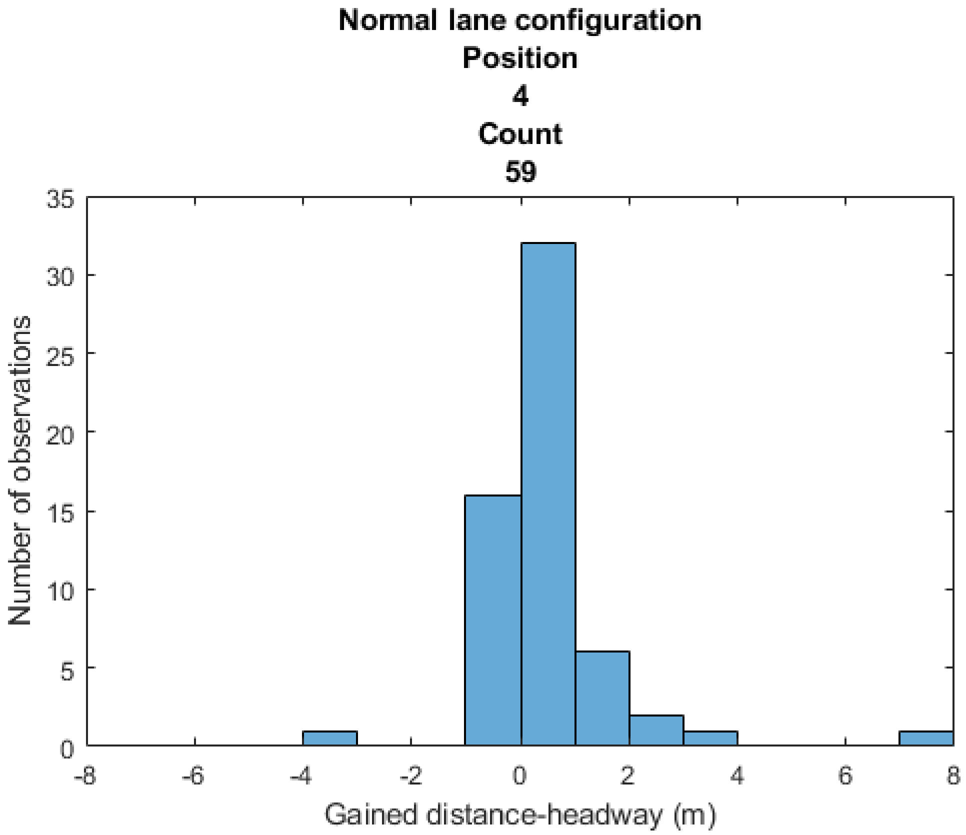
Y. Yuan, B. Goñi -Ros, M. Poppe, W. Daamen and S. Hoogendoorn. *Analysis of bicycle headway distribution, saturation flow and capacity at a signalized intersection using empirical trajectory data.* Transportation Research Record, (2673), 2019.

Appendix A: Gained distance-headway per queue position normal lane configuration






Normal lane configuration
Position
3
Count
58
Number of observations
Gained distance-headway (m)
0
5
10
15
20
25
30
-8
-6
-4
-2
0
2
4
6
8


Normal lane configuration
Position
4
Count
59
Number of observations
Gained distance-headway (m)
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5
10
15
20
25
30
35
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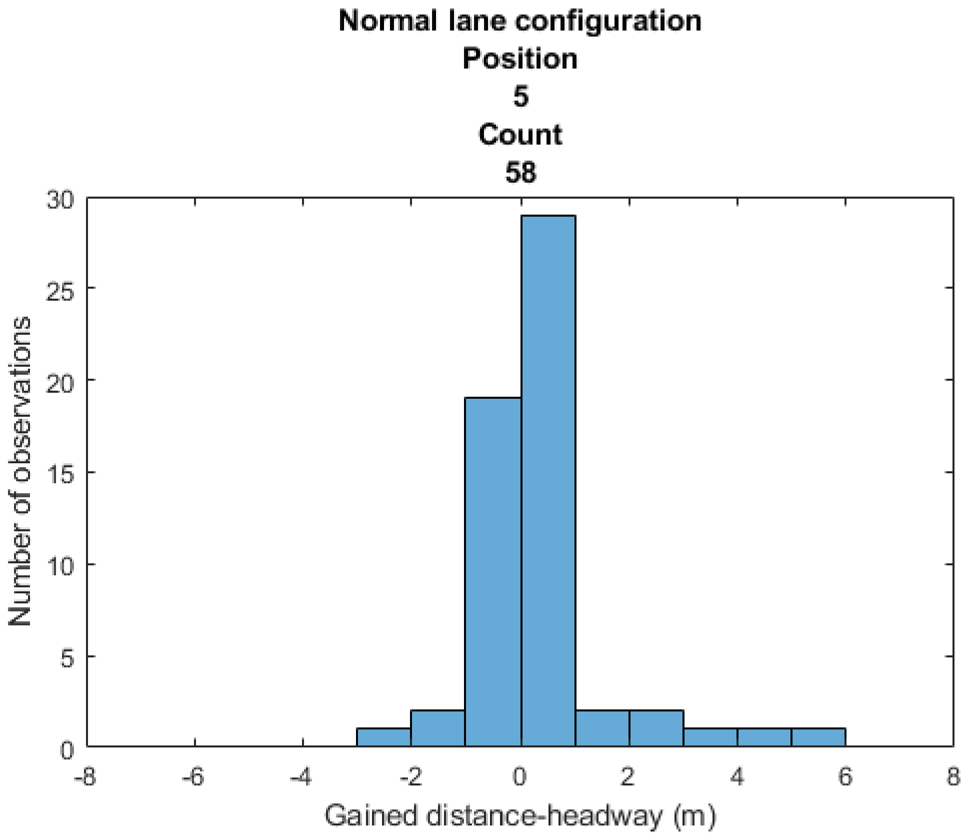
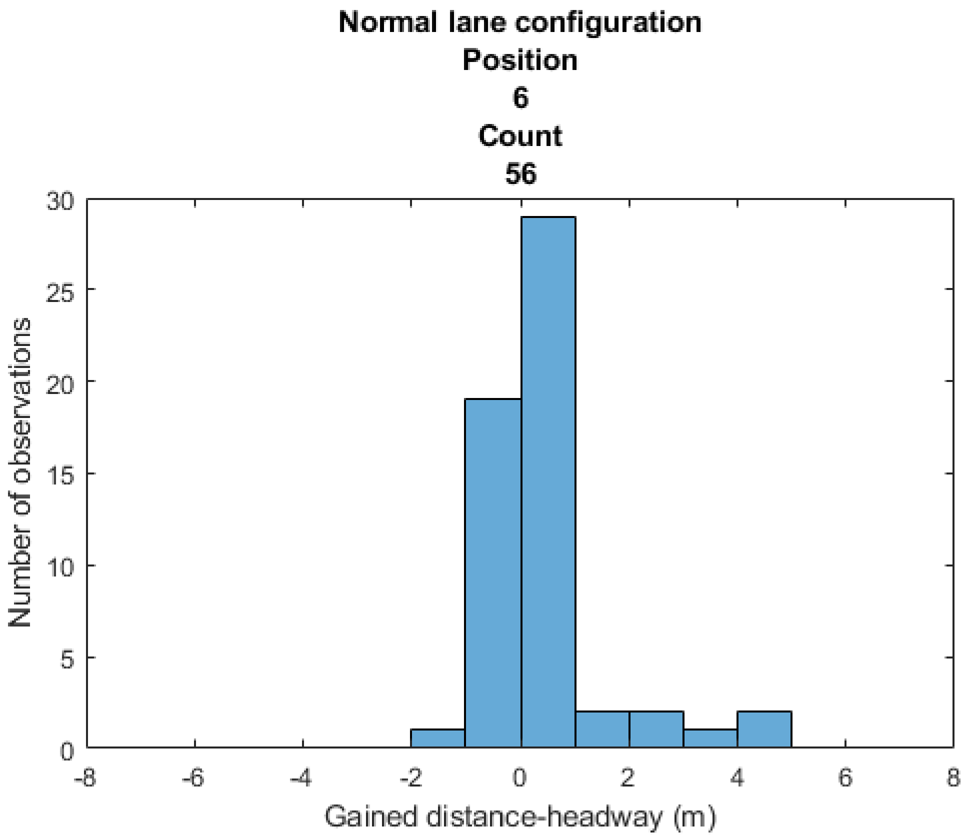
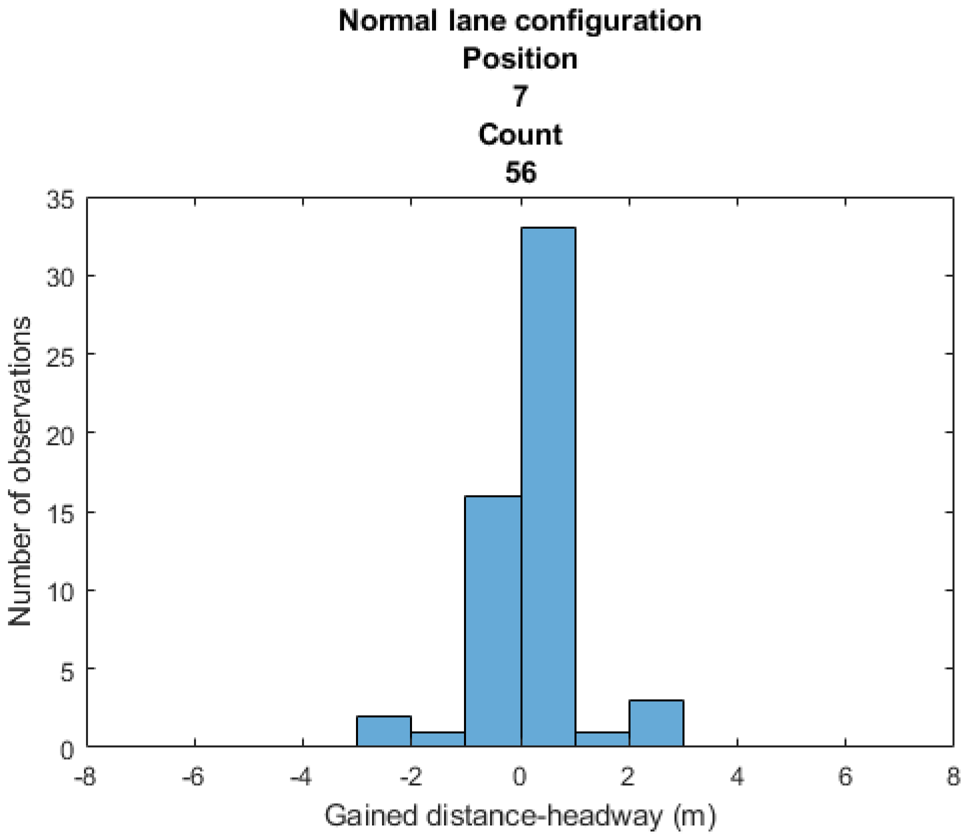
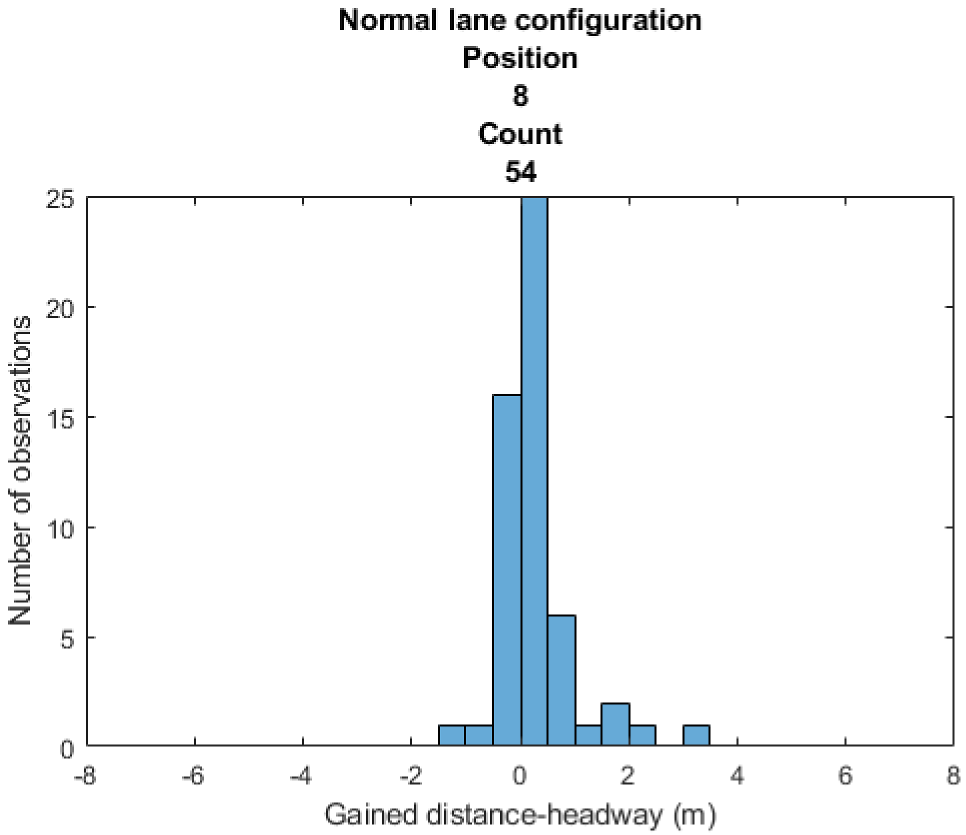
0
2
4
6
8


Normal lane configuration
Position
5
Count
58
Number of observations
Gained distance-headway (m)

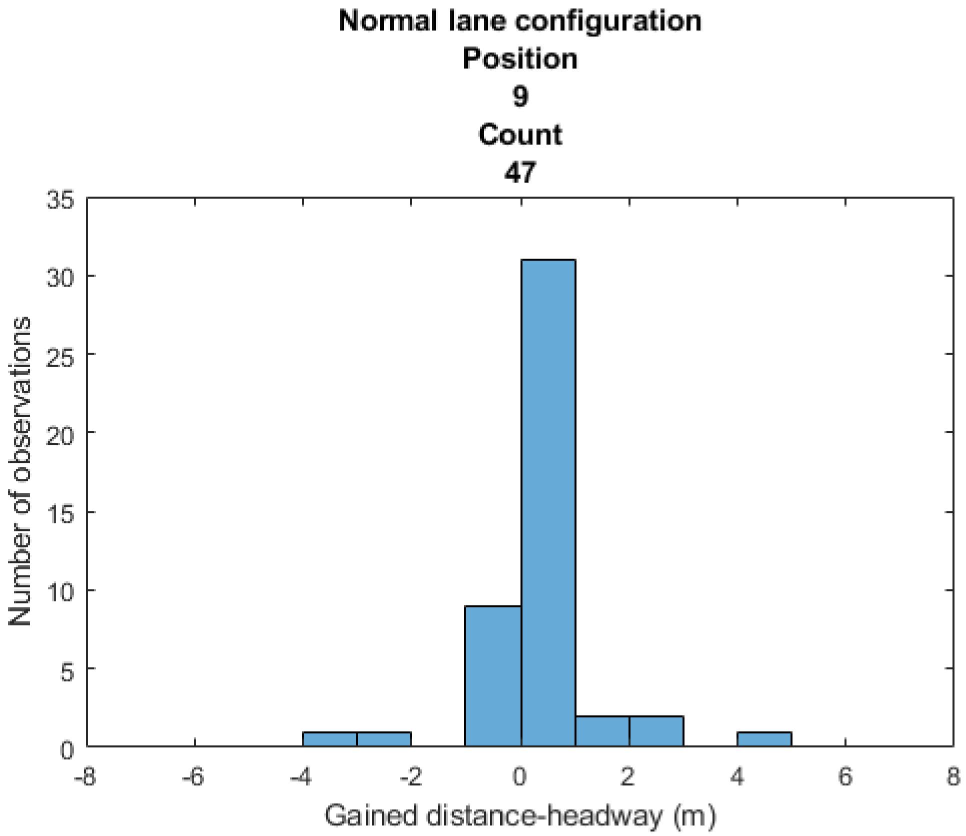

Normal lane configuration
Position
6
Count
56
Number of observations
Gained distance-headway (m)

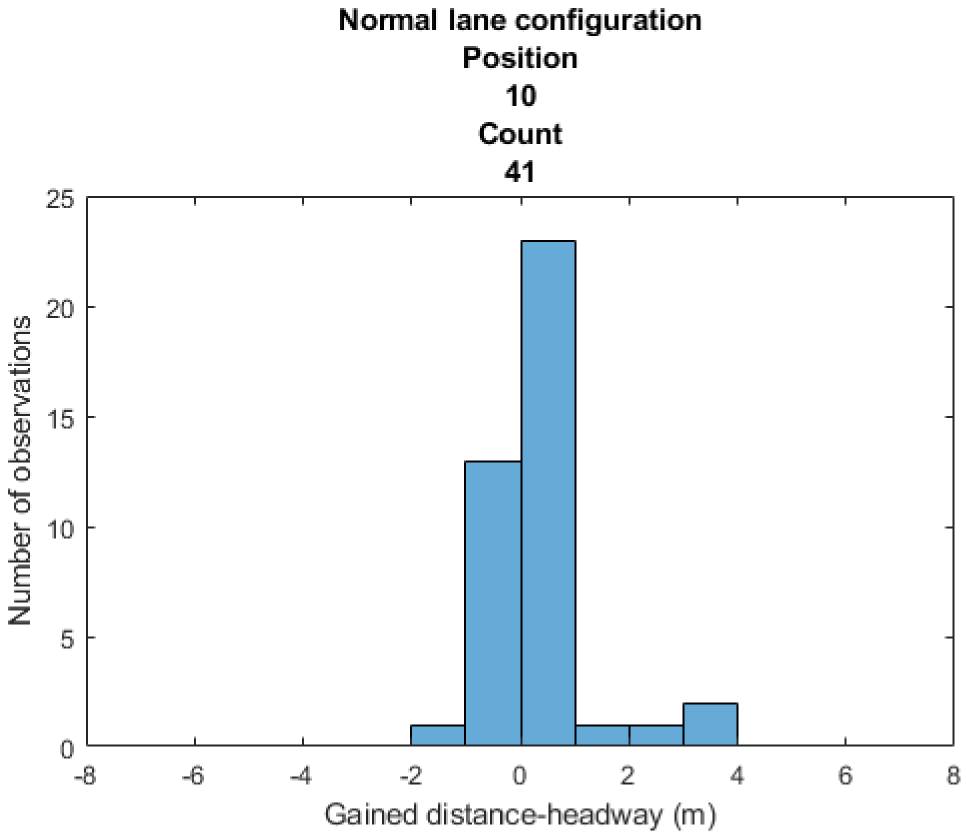


Normal lane configuration
Position
7
Count
56
Number of observations
Gained distance-headway (m)



Normal lane configuration
Position
8
Count
54
Number of observations
Gained distance-headway (m)


Normal lane configuration
Position
9
Count
47
Number of observations
Gained distance-headway (m)


Normal lane configuration
Position
10
Count
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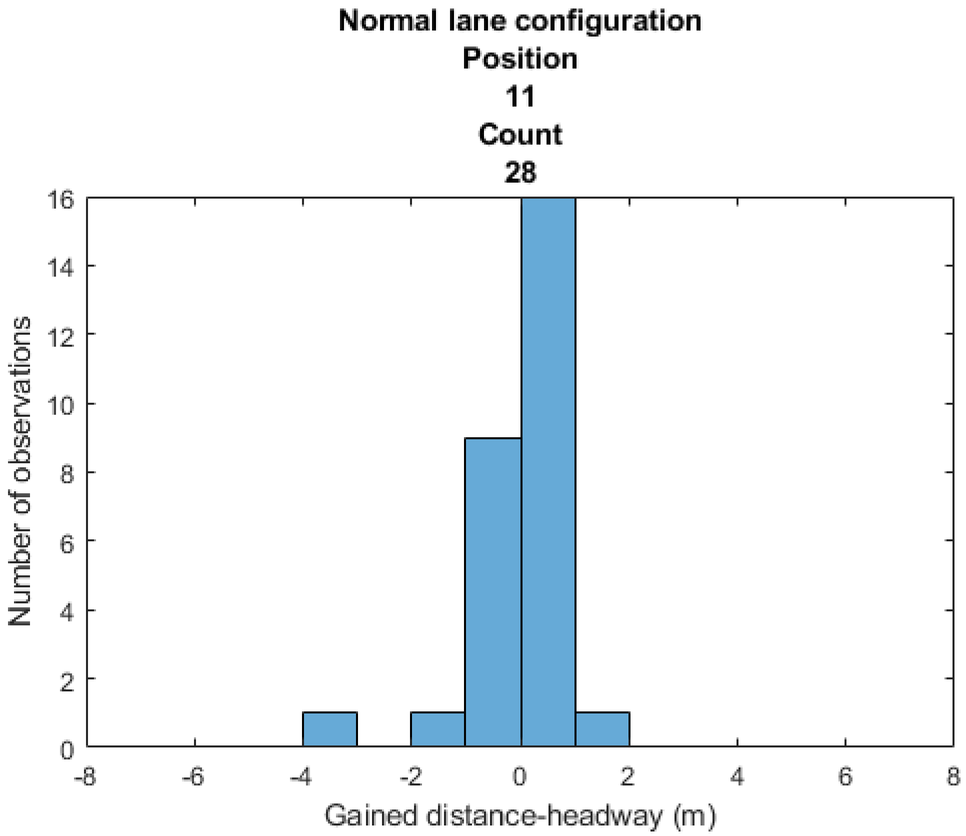
Number of observations
Gained distance-headway (m)


Normal lane configuration
Position
11
Count
28
Number of observations
Gained distance-headway (m)
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14
12
10
8
6
4
2
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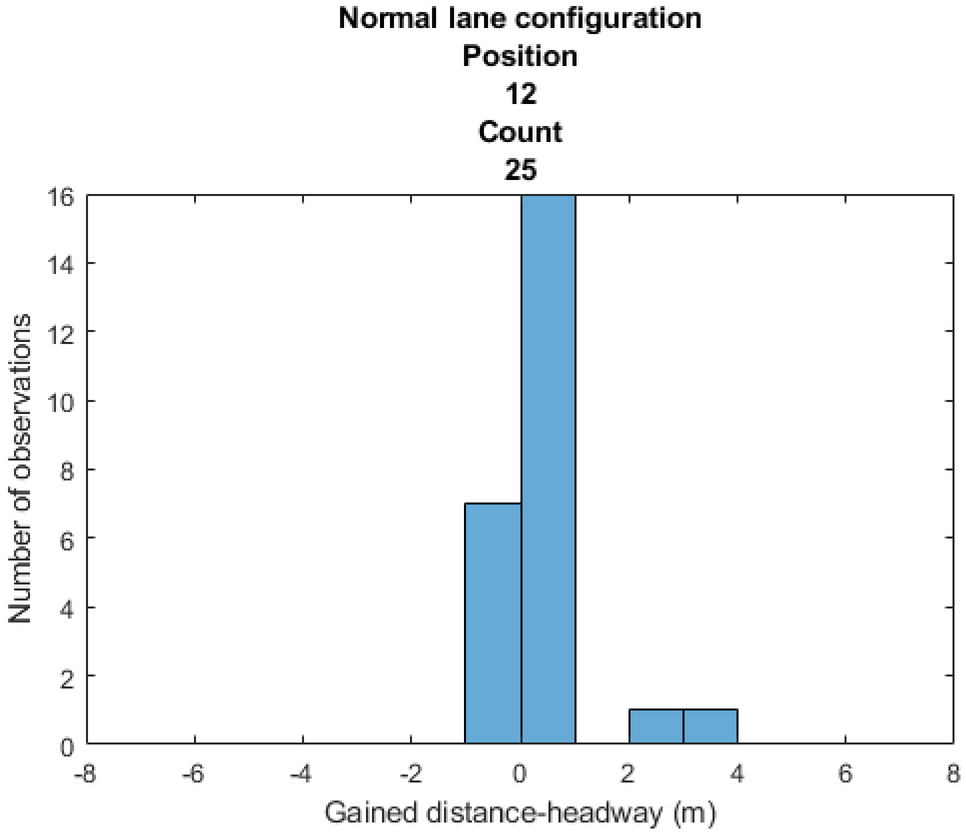
0
2
4
6
8


Normal lane configuration
Position
12
Count
25
Number of observations
Gained distance-headway (m)
16
14
12
10
8
6
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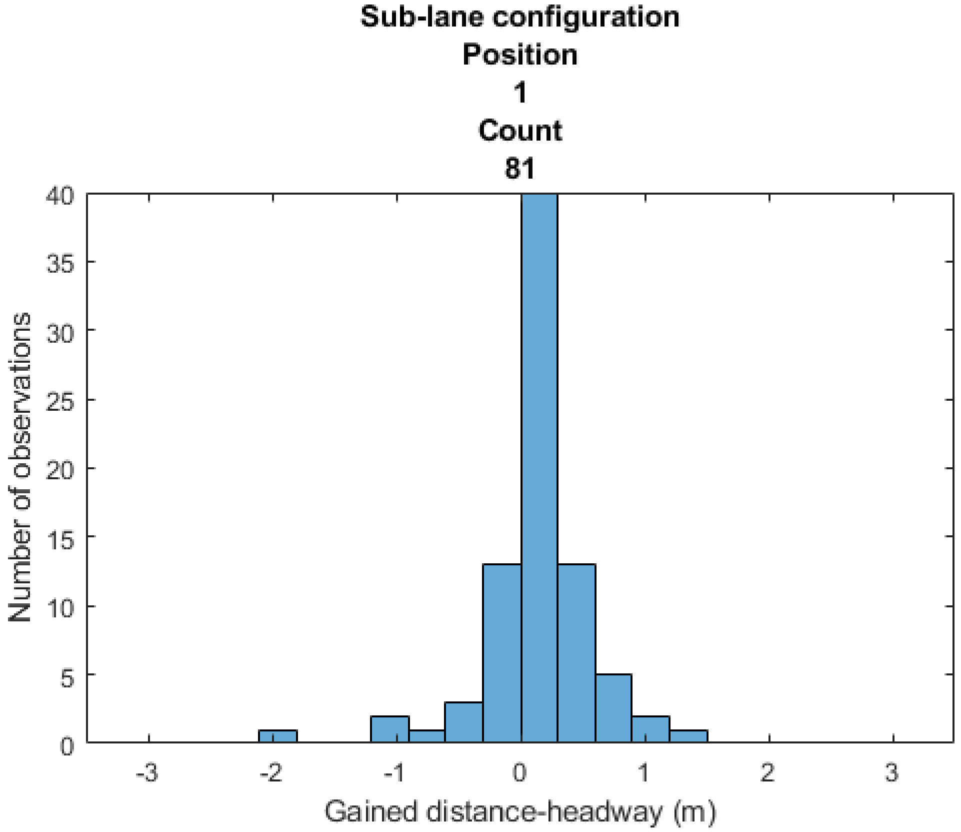
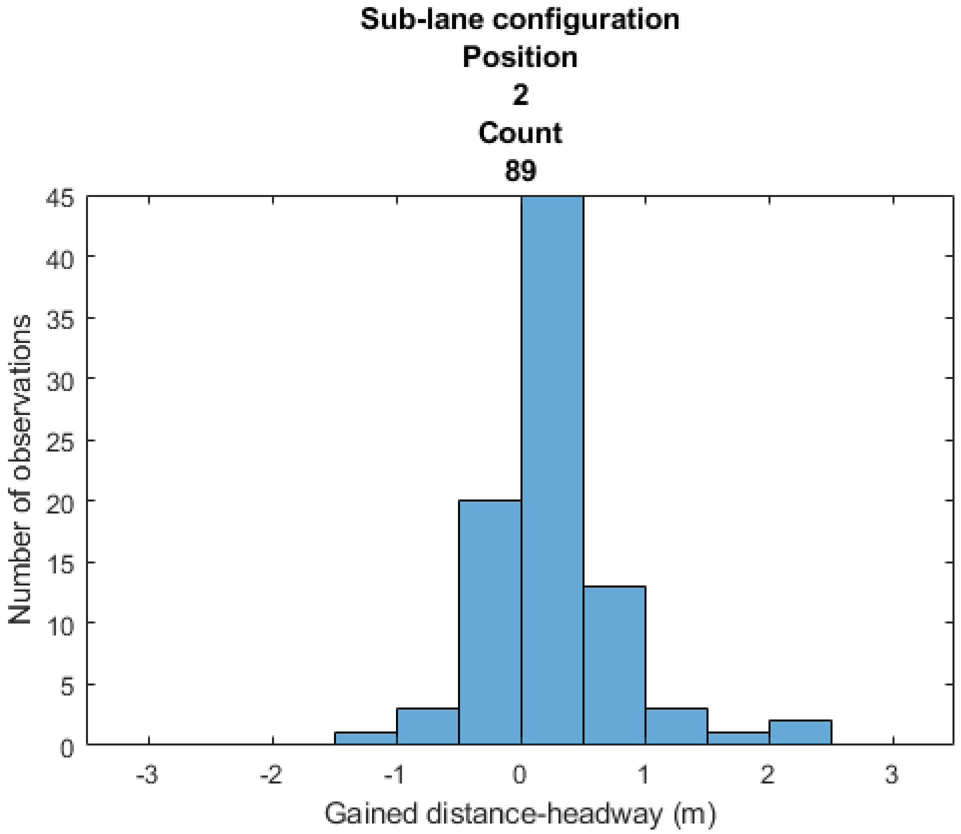
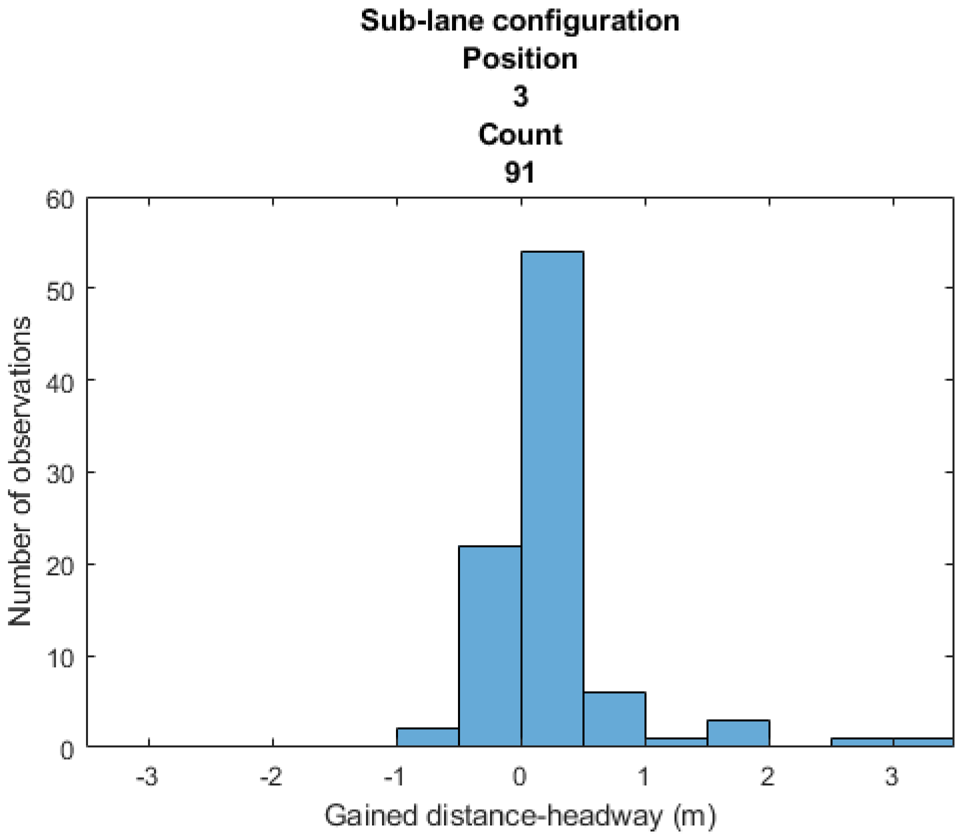
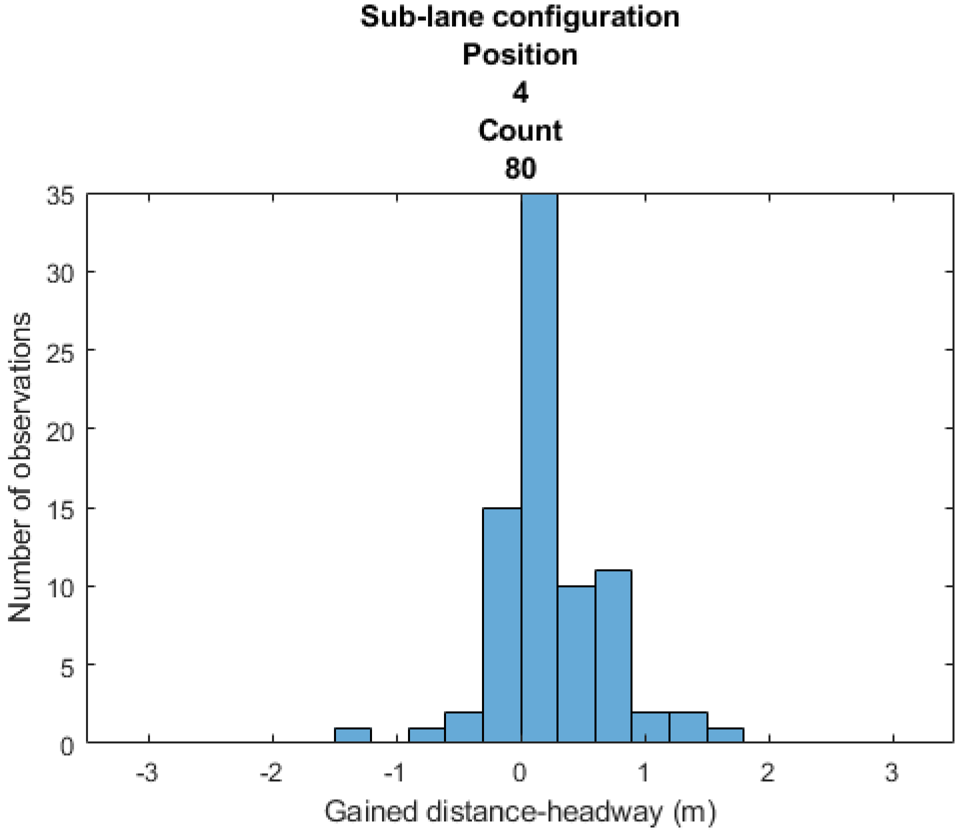
-8
-6
-4
-2
0
2
4
6
8

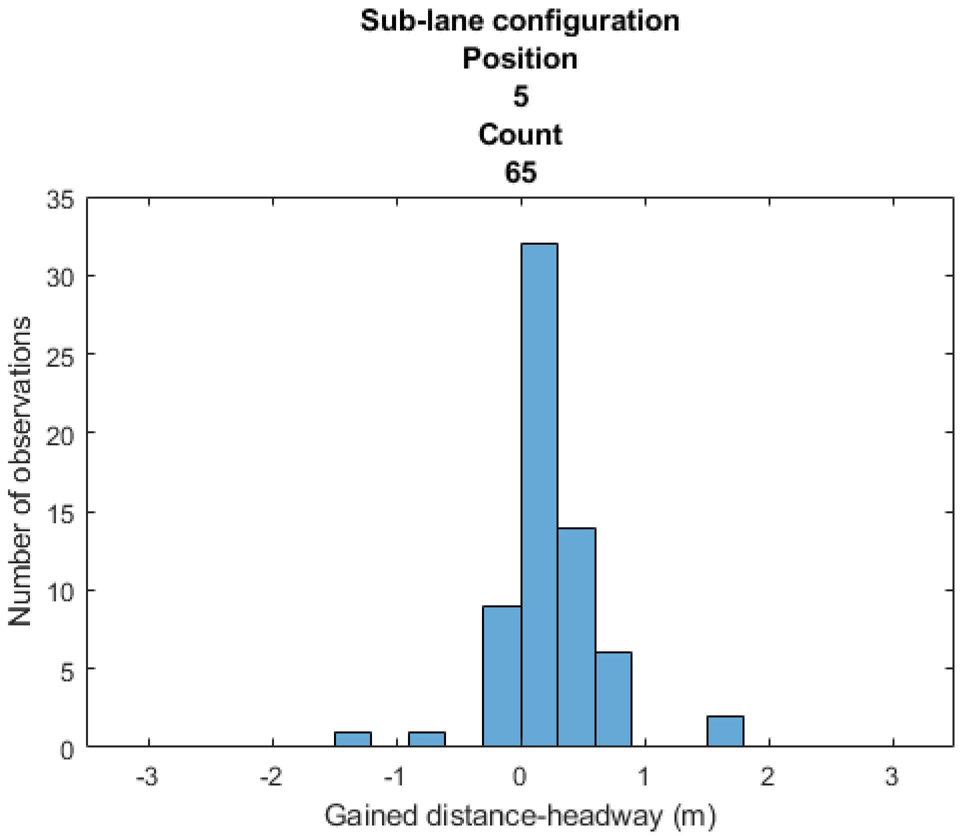
Appendix B: Gained distance-headway per queue position sub-lane configuration

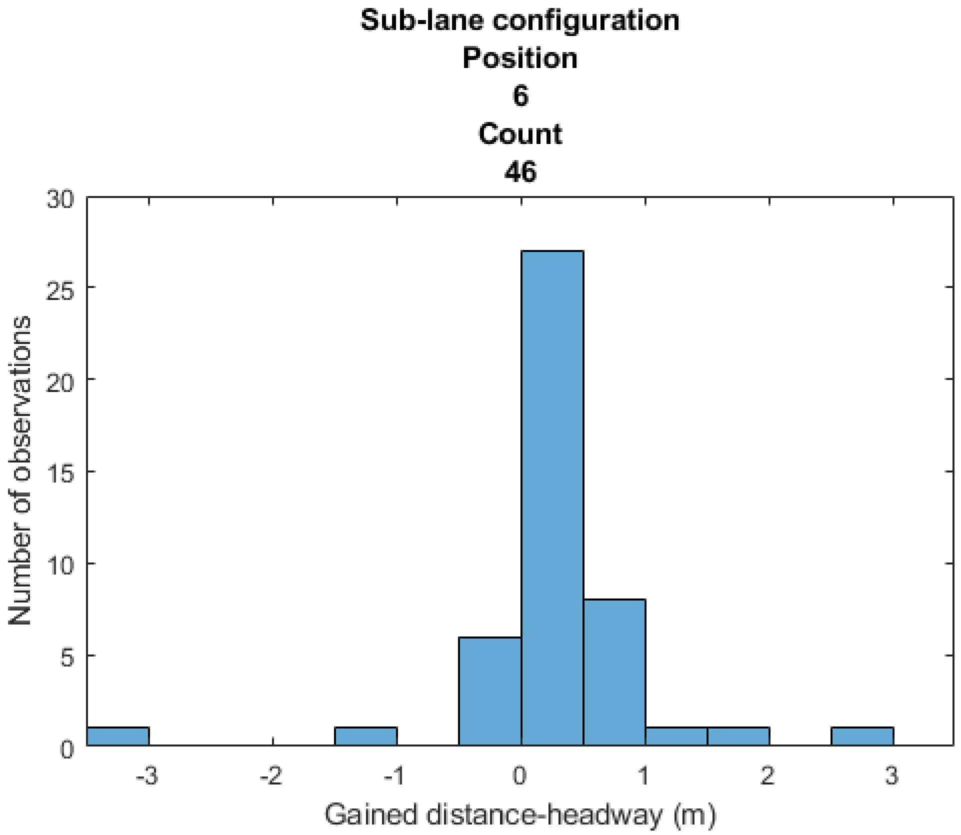


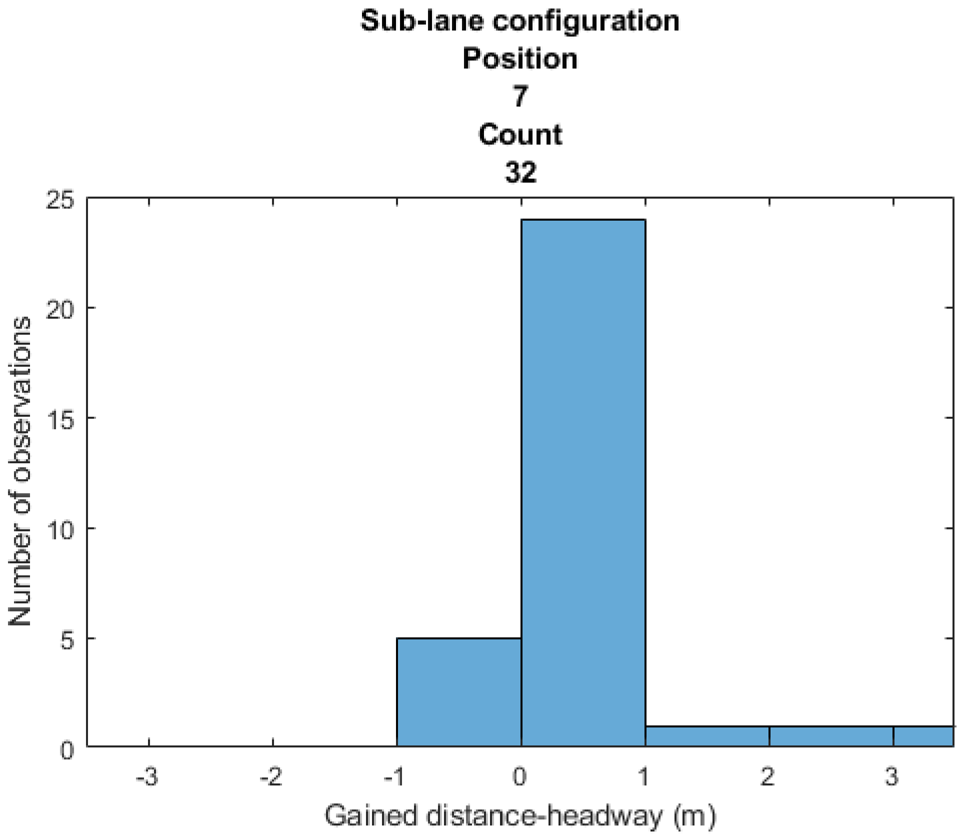



Sub-lane configuration
Position
3
Count
91
Number of observations
Gained distance-headway (m)
60
50
40
30
20
10
0
-3
-2
-1
0
1
2
3


Sub-lane configuration
Position
4
Count
80
Number of observations
Gained distance-headway (m)
35
30
25
20
15
10
5
0
-3
-2
-1
0
1
2
3


Sub-lane configuration
Position
5
Count
65
Number of observations
Gained distance-headway (m)
35
30
25
20
15
10
5
0
-3
-2
-1
0
1
2
3


Sub-lane configuration
Position
6
Count
46
Number of observations
Gained distance-headway (m)
30
25
20
15
10
5
0
-3
-2
-1
0
1
2
3



Sub-lane configuration
Position
7
Count
32
Number of observations
25
20
15
10
5
0
-3
-2
-1
0
1
2
3
Gained distance-headway (m)