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Modeling Sustainable Traffic Behavior: Avoiding Congestion at a Stationary Bottleneck

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Abstract

Sustainable traffic behaviour is increasing in importance as traffic volume rises due to population growth. In this paper, a model for traffic flow at a stationary bottleneck is developed to determine the parameters that cause congestion. Towards this goal, traffic density, speed, and delay were acquired during peak and off-peak periods in the morning and afternoon at a stationary bottleneck in Peshawar, KPK, Pakistan. The morning and afternoon peak periods have high densities, low speeds, and considerable delays. Regression models are developed using this data. These results indicate that there is a linear relationship between density and time at the stationary bottleneck and a negative linear relationship between density and speed. Thus, an increase in density increases the time delay and reduces the speed. I comprehensive traffic delay model is characterized by a stationary bottleneck. The Kolmogorov-Smirnov (KS) test and P-values were used to identify the best-fit distribution for speed and density. The binomial and generalized extreme values are considered the best fits for density and speed. The results presented can be used to develop accurate simulation models for stationary bottlenecks to reduce congestion.

Keywords: Stationary Bottleneck; Target Lane; Traffic Model; Lane Changes; Traffic Congestion; Delay.

1. Introduction

Sustainable traffic behavior can reduce travel time and cost. Traffic congestion in Karachi, Pakistan, is estimated to cost fifty thousand dollars daily [1]. This congestion can be mitigated through sustainable system design, such as real-time optimization of traffic signal patterns [2]. Traffic flow is typically analyzed using speed and density [3]. Speed is the distance traveled by a vehicle in a unit of time, and density is the number of vehicles per unit length in a lane [4]. An increase in density results in a reduction in speed, which increases travel time [5]. The difference between the time for free-flowing traffic and the actual time taken is called the travel time delay [6]. Traffic bottlenecks increase this delay [7]. Traffic bottlenecks can be categorized as stationary or moving [8, 9]. At moving bottlenecks, vehicles follow slow vehicles due to the unavailability of space to overtake. As a result, they adopt the velocity of the leading vehicles, which is known as the platoon velocity [9, 10]. At stationary bottlenecks, vehicles are forced to change lanes because of

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closures due to construction, accidents, or other events [11–13]. They tend to move toward less congested lanes (target lanes) in order to maintain their speed. Distance headway is the distance between two successive vehicles and is a key indicator of lane change [14]. Time headway is the time required to align with leading vehicles and is mainly influenced by speed and traffic flow [15]. The distance headway can be determined from the time headway [16].

Congestion due to high volumes of traffic is a major problem in urban areas [17]. Pedestrians crossing roads contribute to congestion as their speeds are comparatively slow [18]. Midblock crosswalks have been installed at intersections to improve pedestrian safety but have a negative impact on traffic capacity and progression [19]. Congestion increases the travel time delay and has a significant economic and environmental impact [20]. Commercial activities are slower and emissions are higher in congestion compared to free-flow conditions [21]. Improvements in public transport reduce the number of vehicles, which lowers vehicle emissions [22]. Increasing the number of road lanes to mitigate congestion is not an economical or effective solution. A better approach is to examine the corresponding traffic behavior based on parameters such as density, speed, and travel time delay and then take appropriate actions [23].

Traffic flow has been studied at both the macroscopic and microscopic levels [24]. Macroscopic models provide information on the overall traffic conditions such as congestion, queue formation, and delay [25]. The parameters typically considered are speed, density, and flow. Microscopic models consider individual vehicles and their interactions with the surrounding environment [26]. Real data is required for accurate modelling [27]. The density and speed in a target lane are the stimuli for driver action. When the driver determines an acceptable distance between vehicles, a lane change can occur [28]. The time required for a lane change is the time for a driver to notice the opportunity, make a decision, and then take action by adjusting their speed [29]. A successful lane change affects the equilibrium traffic flow in the target lane [30]. High densities and speeds limit the lane change opportunities [31]. Lane changes are categorized as mandatory or discretionary [32].

In this study, a lane change model is proposed to analyze the parameters that cause travel time delay at stationary bottlenecks. The density and speed in a target lane are affected by a successful lane change. Pedestrians crossing the street increase the delay. To determine these parameters, real-time data is obtained during peak and off peak periods. The distributions of density and speed in the peak and off-peak periods are determined using the Kolmogorov-Smirnov (KS) test and P-values. These distributions are used to study traffic flow behavior. The results obtained can be used to help mitigate traffic congestion at stationary bottlenecks.

2. Lane Change Model

If s is the road section length and v is vehicle speed, then the time to traverse the road section in uncongested traffic with no pedestrians is:

$$\frac{s}{v} \tag{1}$$

The time for a lane change can be expressed as [33]:

$$t_T \propto \frac{1}{v} \tag{2}$$

The time required to find an acceptable gap in the target lane is

$$t_A \propto (\rho_T, v_T) \tag{3}$$

where, ρ_T is the target lane density and v_T is the target lane speed. A large ρ_T makes it difficult to change lanes and thus more time is required to find an acceptable gap in the target lane, which results in congestion [34]. Thus, t_A increases with density. The distance headway is larger in free flow traffic and an acceptable gap can more easily be found [34]. A lane change is easier when the speed in the target lane is lower, and it is difficult to change lanes with a small relative speed difference between lanes and a large speed in the target lane [30]. A lane change perturbs the flow in the target lane and can create congestion and a queue of vehicles. The increased density due to merging vehicles results in reduced lane speed and increased time headway. The queue created in the target lane is proportional to ρ_T [35] so the time required to attain equilibrium flow after a successful lane change can be expressed as:

$$t_E \propto (\rho_T, v_T) \tag{4}$$

Pedestrians crossing a road also affect traffic flow. The time required to attain the equilibrium flow in the presence of pedestrians depends on the number of pedestrian N_P, road width w, and pedestrian speed V_p while crossing the road which gives:

$$t_P \propto \frac{N_P\, w}{V_P} \tag{5}$$

The total time required to change a lane and attain equilibrium flow at a stationary bottleneck is then:

$$T = \frac{s}{v} + t_A + t_T + t_E + t_P \tag{6}$$

$$T = \frac{s}{v} + t_A\,(\rho_T\,, v_T) + t_T\,(\frac{1}{v}) + t_E\,(\rho_T\,, v_T) + t_P(\frac{N_P\, w}{V_P}) \tag{7}$$

Thus, a high density ρ_T and speed v_T in the target lane decrease the probability of finding an acceptable gap. After finding an acceptable gap, higher speed vehicles take less time to move into the target lane. Merging vehicles increase ρ_T which results in an increased time headway and queue length. Further, pedestrians crossing the road reduce the speed and increase the time headway. Traffic flow decreases with ρ_T which increases queue length, and this increases with N_P.

3. Methodology

The construction of the Bus Rapid Transit (BRT) system in Peshawar, Pakistan, resulted in stationary bottlenecks at several locations which created large travel time delays. This is because the number of lanes was reduced which resulted in demand that exceeded the road capacity. To study the corresponding traffic behavior, a stationary bottleneck located at Arbab Road Stop, Peshawar, with coordinates (34.004725 N, 71.503731 E) was selected and is shown in Figures 1 and 2. Four lanes dedicated for traffic in each direction are reduced to three lanes as one lane is used by BRT Peshawar. The road width was further reduced by one lane due to underpass construction. Thus, the road width was reduced by 50%. The length of the road segment observed was 100 m and this is shown in yellow in Figure 1. This segment was divided into 10 m intervals to accurately determine vehicle positions. Two digital cameras were installed on top of a plaza at a height of 25 m to cover the entire road segment. All cameras were synchronized and the video was recorded at a rate of 25,000 frames per second (fps).

Figure 1. The location of the data collection points on Google Maps

Figure 2. The location of the stationary bottleneck at Arbab Road Stop, Peshawar, with coordinates (34.004725 N, 71.503731 E)

Traffic data was collected from 9:00 AM to 12:00 AM, 2:00 PM to 3:00 PM, and 3:00 PM to 6:00 PM from Monday to Friday (March 4, 2019 to March 8, 2019). A total of 250 vehicles were observed during both the morning (9:00 AM to 12:00 PM) and afternoon (3:00 PM to 6:00 PM) peak traffic periods. During these times, many people are travelling to or from locations such as work, educational institutions, lunch, or shopping as shown in Figure 3. This results in high density, low speeds, and significant travel time delay. The off peak time traffic and the interaction with pedestrian is shown in Figures 4 and 5. The afternoon hour 2:00 PM to 3:00 PM is an off peak time.

Figure 3. Entrance and exit points of the 100 m section of road

Figure 4. Off peak traffic conditions

Figure 5. Interaction with pedestrians at the observed location

The travel time is obtained from the difference in vehicle exit and entrance times, and this is divided by the distance, i.e. 100 m, to obtain the speed v_T. The density ρ_T is the number of vehicles per meter in a lane and was obtained by counting the number of vehicles in the video frames from the cameras. The pedestrian speed was calculated by dividing the road width of 3.7 m by the time taken to cross. The compiled data is analysed using Excel and the Statgraphics package. A lane change model is then developed which includes all the time delay parameters. A flow chart of the methodology used in this study is given in Figure 6.

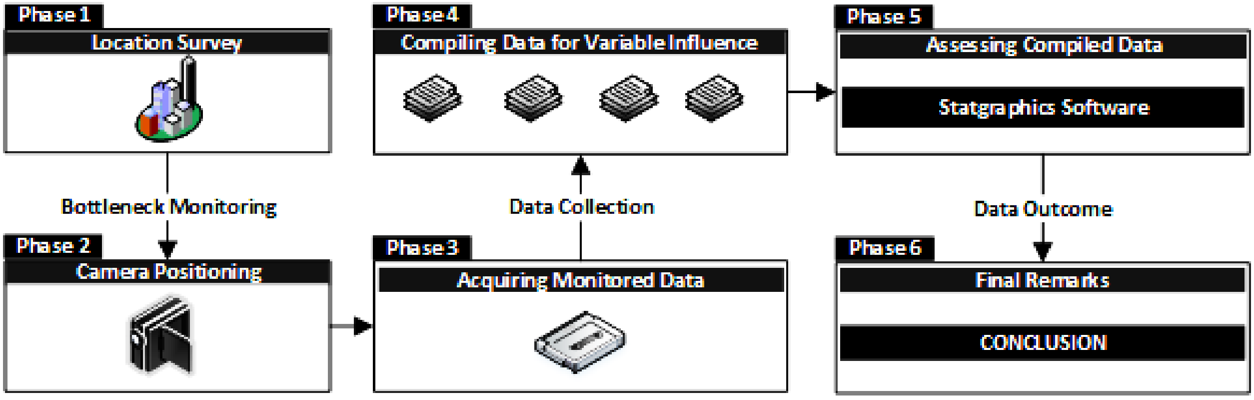

Figure 6. Flow chart of the methodology employed

P-values are used to determine whether the difference between observed and expected values is statistically significant [36]. The Kolmogorov-Smirnov (KS) test is a goodness of fit test. This test gives the distance between an empirical cumulative distribution function (ECDF) and a model cumulative distribution function (MCDF) [37]. It determines whether the observed data is adequately modelled by the given distribution. For the KS test, the observed data is arranged in ascending order $x_1, x_2, x_3, \dots, x_N$ and the ECDF is defined as:

$$E(x) = n/N \tag{8}$$

where n is number of observations less than or equal to x. The KS statistic is the maximum absolute difference between the MCDF and ECDF values [38]:

$$D = \max |\, F_o\,(x) - E(\mathrm{x})| \tag{9}$$

where $F_o\,(x)$ is the MCDF. The KS test is performed at a 5 percent level of significance to ensure strong evidence to reject or accept the null hypothesis [32, 33]. The KS test critical value for this level of significance is $1.36/\sqrt{N}$. The null hypothesis (data comes from the model distribution), is accepted when the KS statistic is lower than the critical value. The best fit distributions for density and speed are obtained using Easy Fit based on the KS test. Easy Fit is a data analysis package used to solve business and scientific problems. It helps users visualize data, explore relationships, and identify trends.

4. Parameter Statistics

The mean of the travel time in the morning and afternoon is 55.92 s and 56.97 s, respectively, as indicated in Table 1. In the off peak period, the average time is 11.34 s so the corresponding average speed is 8.82 m/s. The travel time delay due to the stationary bottleneck is then 55.92 – 11.34 = 44.58 s and 56.97–11.34 = 45.63 s. The maximum travel time in the morning and afternoon is 66.60 s. The morning and afternoon peak periods have high density, low speeds, and large travel time delays. The design speed for the road section considered is 12.5 m/s, so the time taken by a vehicle in the ideal case is 8.00 s.

Table 1. Time, Density, and Speed Statistics

Parameter	Mean	Median	Variance	Std. Dev.	Maximum	Minimum
Number of Observations	250	250	250	250	250	250
Morning Time (s)	56.74	57.00	10.76	3.28	66.60	44.00
Afternoon Time (s)	57.13	57.26	11.96	3.46	66.00	44.68
Off-Peak Time (s)	11.52	11.00	3.34	1.83	16.00	8.00
Ideal Time (s)	8.00	8.00	0.00	0.00	8.00	8.00
ρ_T, Morning	17.41	17.00	3.26	1.80	22.00	13.00
ρ_T, Afternoon	16.96	17.00	3.56	1.89	22.00	11.00
v_T , Morning	1.77	1.75	0.01	0.11	2.27	1.50
v_T , Afternoon	1.76	1.75	0.01	0.11	2.24	1.52

The peak, off peak, and ideal travel time are shown in Figure 7. This illustrates that the travel time delay is significant, so the target lane flow is affected by lane changes at stationary bottleneck. The density ρ_T significantly increases the travel time as shown in Figure 8. The density increases while the speed decreases as shown in Figure 9, resulting in long queues at the stationary bottleneck. The linear relationship between time and density and the negative linear relationship between speed and density are the main factors influencing delay at the stationary bottleneck. The time delay due to pedestrian crossings the road is given by Equation 5. The minimum, average, and maximum time taken by a pedestrian observed from the recorded data as shown in Figure 6 are 5, 6, and 7 s, respectively. The width of the two-lane road is $w = 7$ m and the average speed V_P from Equation 5 is 1.16 m/s. The stop-and-go conditions due to pedestrians also increase the delay at stationary bottlenecks.

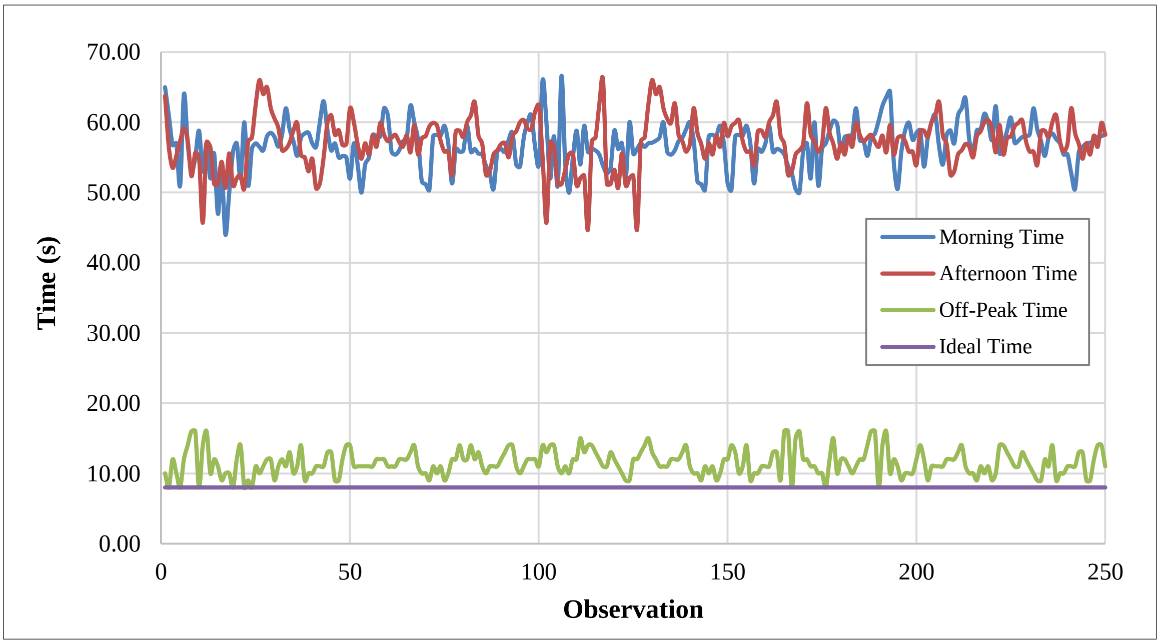

Figure 7. Morning, afternoon, off-peak, and ideal travel times

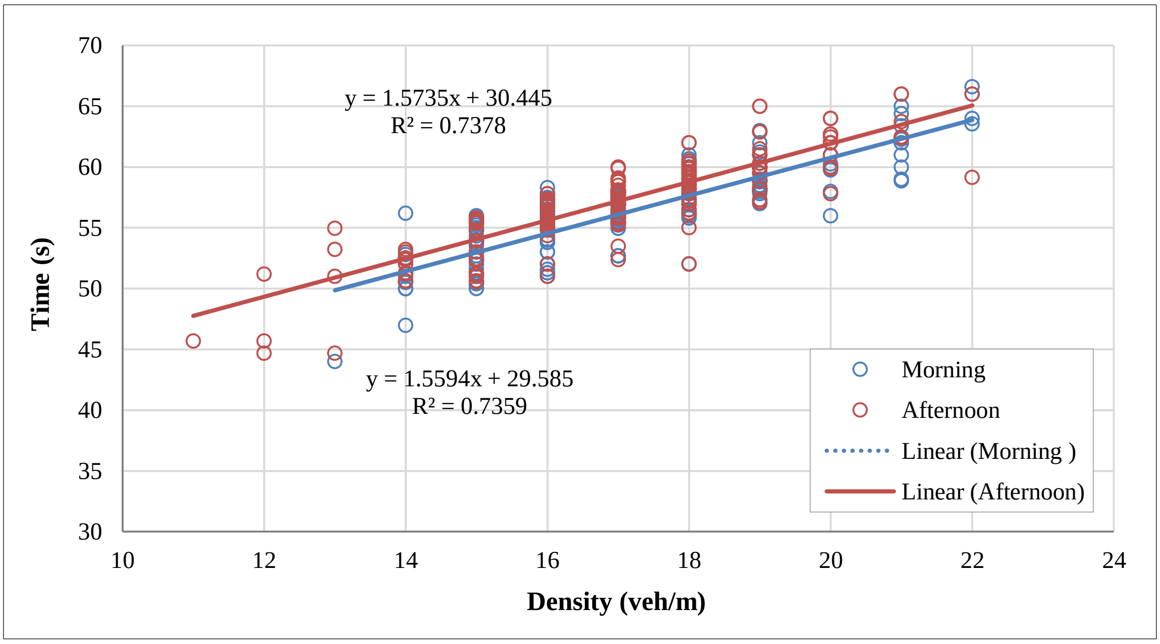

Figure 8. Traffic density and travel time

It is observed that vehicles take close to 60 s to cover the road section during the peak period while the in off-peak period it is almost 11 s. In the ideal case where a vehicle is free to move at the design speed of 45 km/h (12.5 m/s), it would take just 8 s to cover the same distance. The target lane density ρ_T and speed v_T in the morning and afternoon peak periods are almost 17 and 1.75 m/s, respectively, i.e., about 17 vehicles in the 100 m road section. The standard deviation of ρ_T indicates that the variation in values is maximum in the afternoon peak period while the variation in v_T in the morning and afternoon peak periods is almost the same.

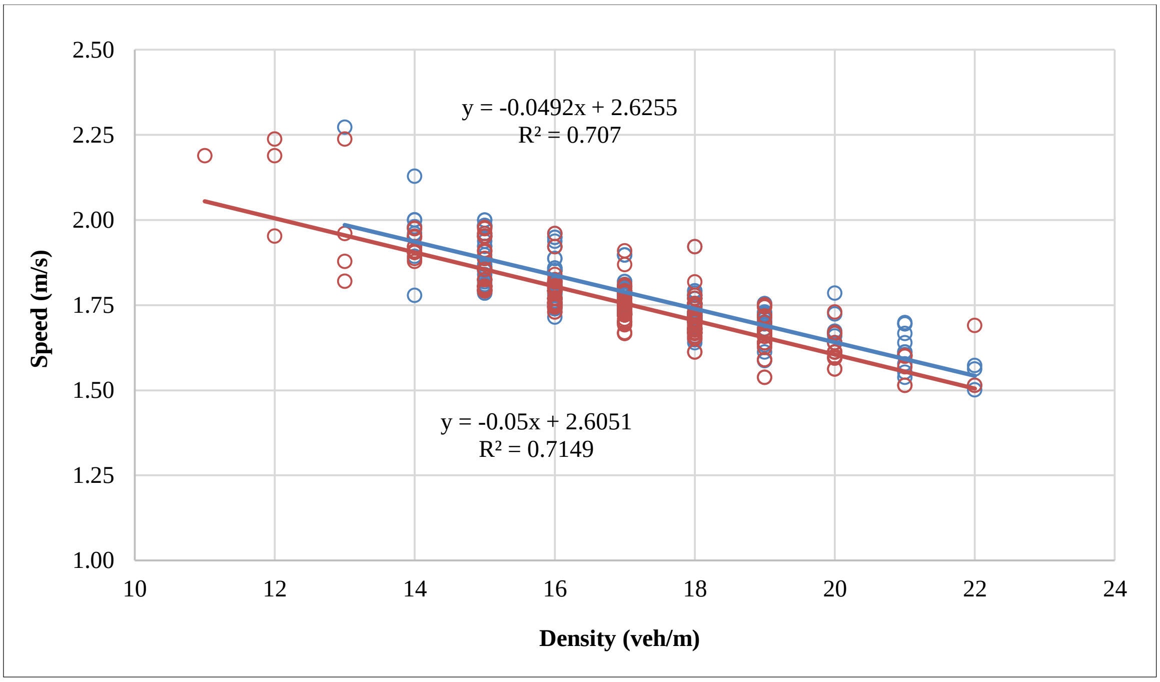

Figure 9. Traffic speed versus density

Figure 8 shows a positive linear relationship between travel time and density for the morning and afternoon peak periods. A larger density causes greater delay. The value of R^2 for the density and time in these periods are 0.735 and 0.739, respectively. These results show that about 70% of the variation is explained by this relationship. Figure 9 shows a negative linear relationship between ρ_T and v_T for the morning and afternoon peak periods. A larger density results in a lower speed. The value of R^2 for ρ_T and v_T in these periods are 0.707 and 0.7014, respectively. This shows that about 70% of the variation is explain by this relationship.

The probability density functions (PDFs) of traffic density in the morning and afternoon are given in Figures 10 and 11, respectively, and the corresponding cumulative density functions (CDFs) are given in Figures 12 and 13. The Kolmogorov-Smirnov test is a statistical test that is used to determine the difference in the distributions of two samples. Table 2 presents the parameters of the best-fit density distributions ranked according to the KS test statistic. This shows that the binomial distribution is the best-fit for the morning and afternoon densities with KS test statistic values 0.054 and 0.068, respectively, and n and p values given in the table. The 80th percentile values of density are 19 and 18 as shown in Figures 12 and 13, respectively. The generalized extreme value is the best fit distribution for the morning and afternoon speeds with KS test statistic values 0.08 and scale, location, and shape parameters σ, μ, and k given in the table. Figures 14 and 15 show that the 80th percentile values are 1.88 m/s.

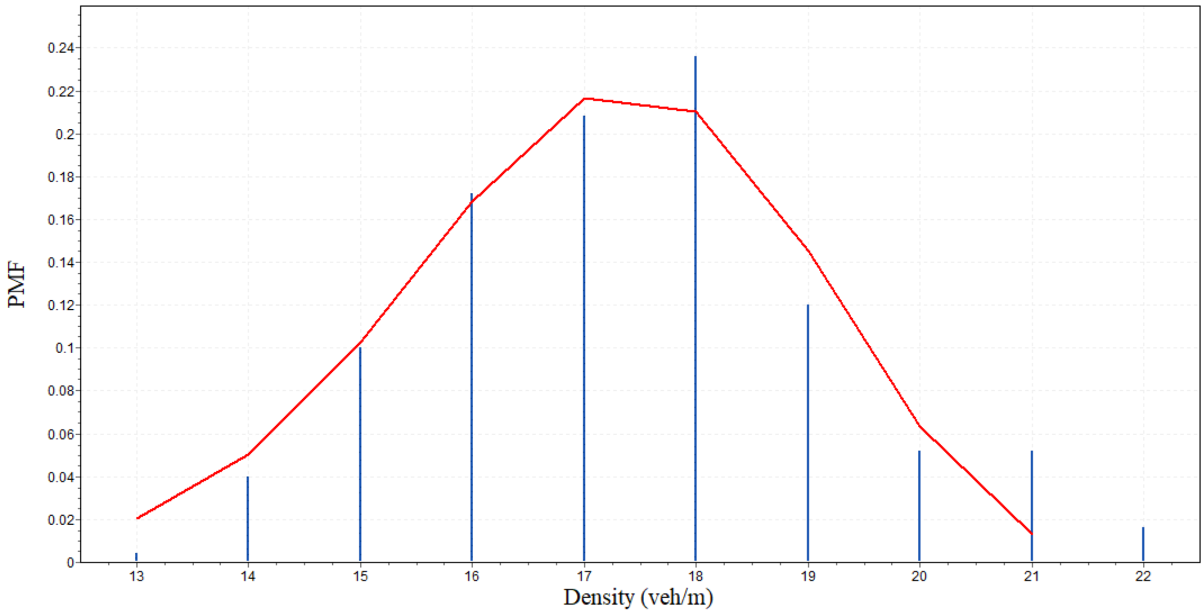

Figure 10. PDF of traffic density in the morning

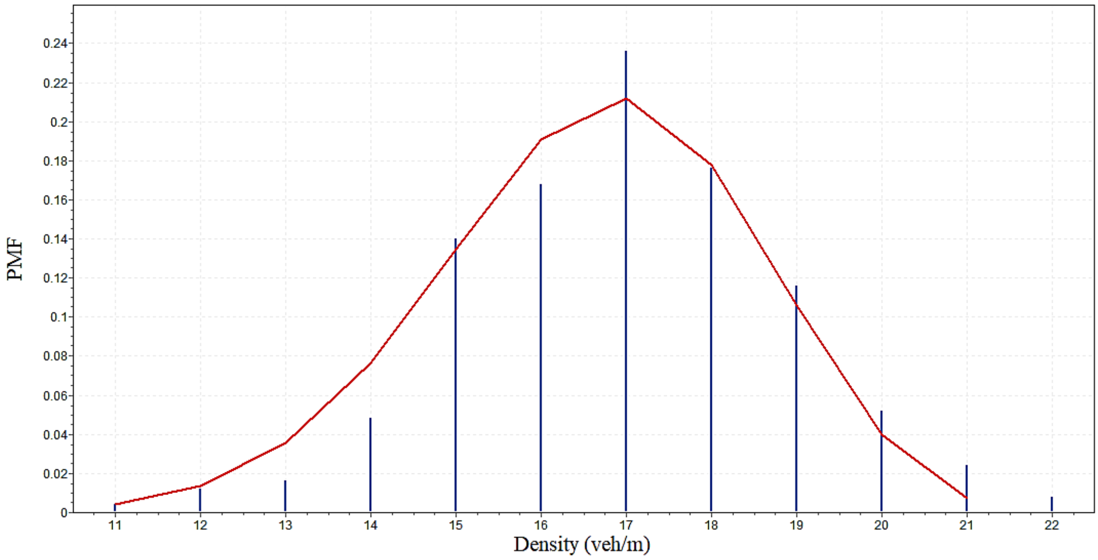

Figure 11. PDF of traffic density in the afternoon

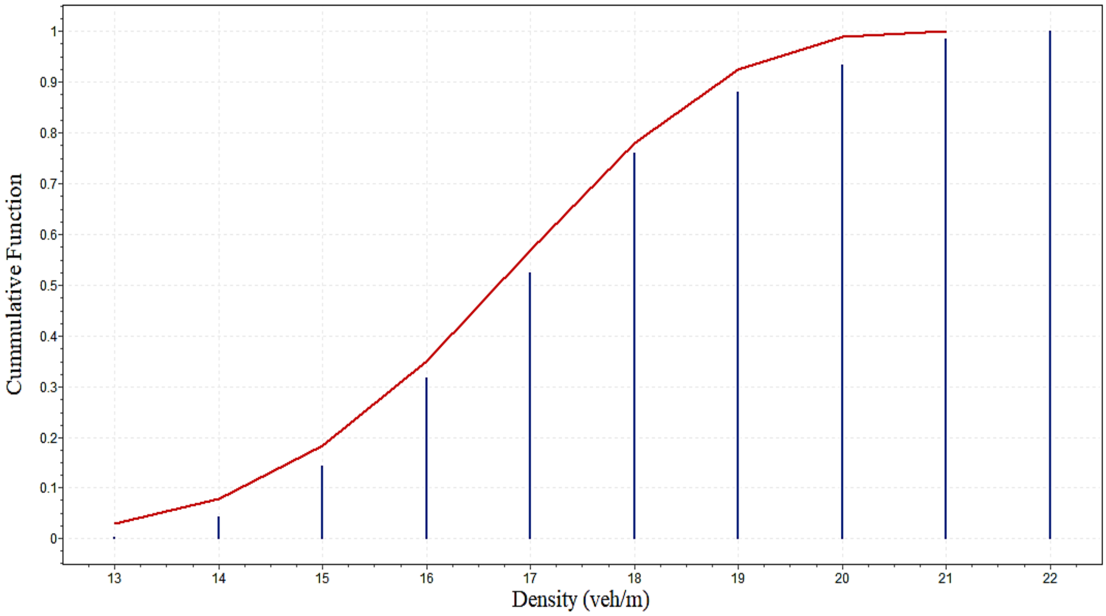

Figure 12. CDF of traffic density in the morning

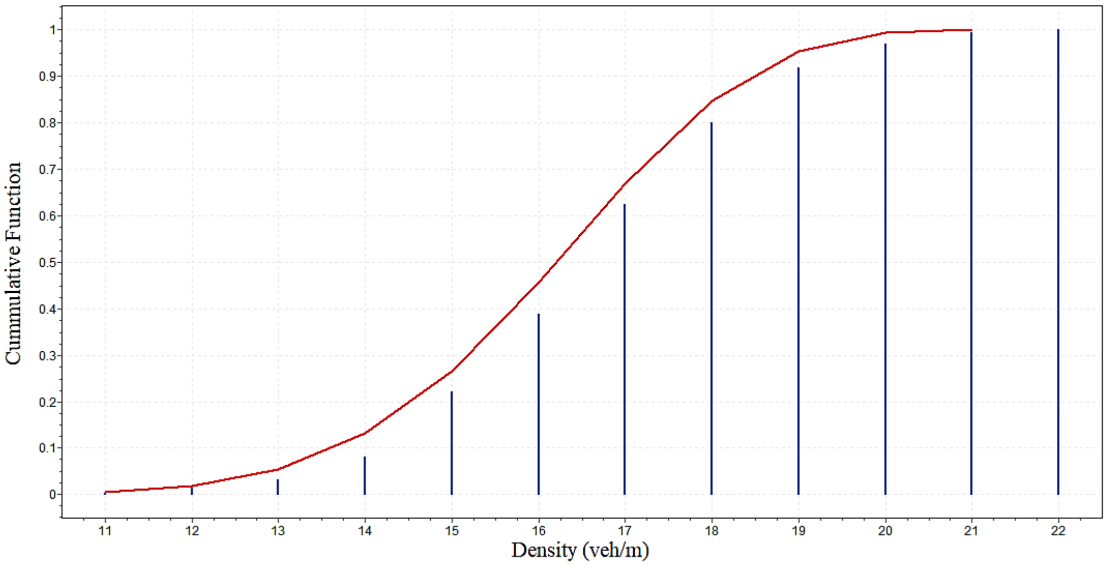

Figure 13. CDF of traffic density in the afternoon

Table 2. Best Fit Distributions for Traffic Density and Speed

Distribution Analysis	Distribution	KS Value	Parameters
ρ_T, Morning	Binomial	0.054	n = 21, P = 0.813
ρ_T, Afternoon	Binomial	0.068	n = 21, P = 0.790
v_T , Morning	Generalized Extreme Value	0.08	σ = 0.086, μ = 1.723, k = 0.0639
v_T , Afternoon	Generalized Extreme Value	0.08	σ = 0.0905, μ = 1.711, k = 0.069

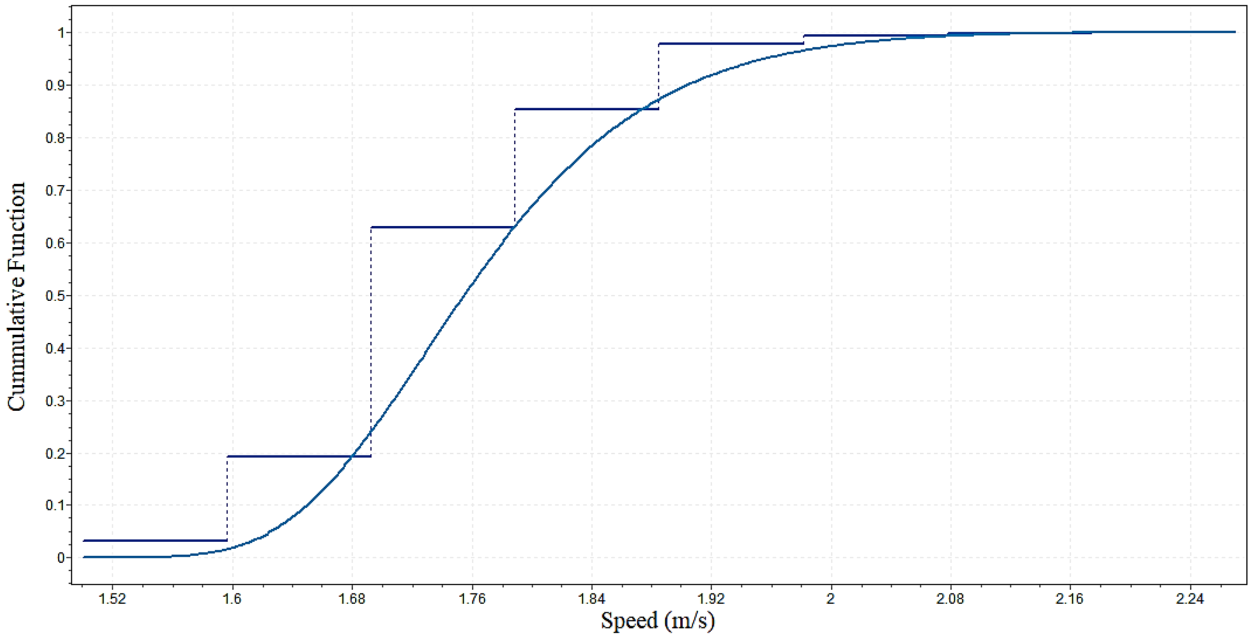

Figure 14. CDF of speed in the morning

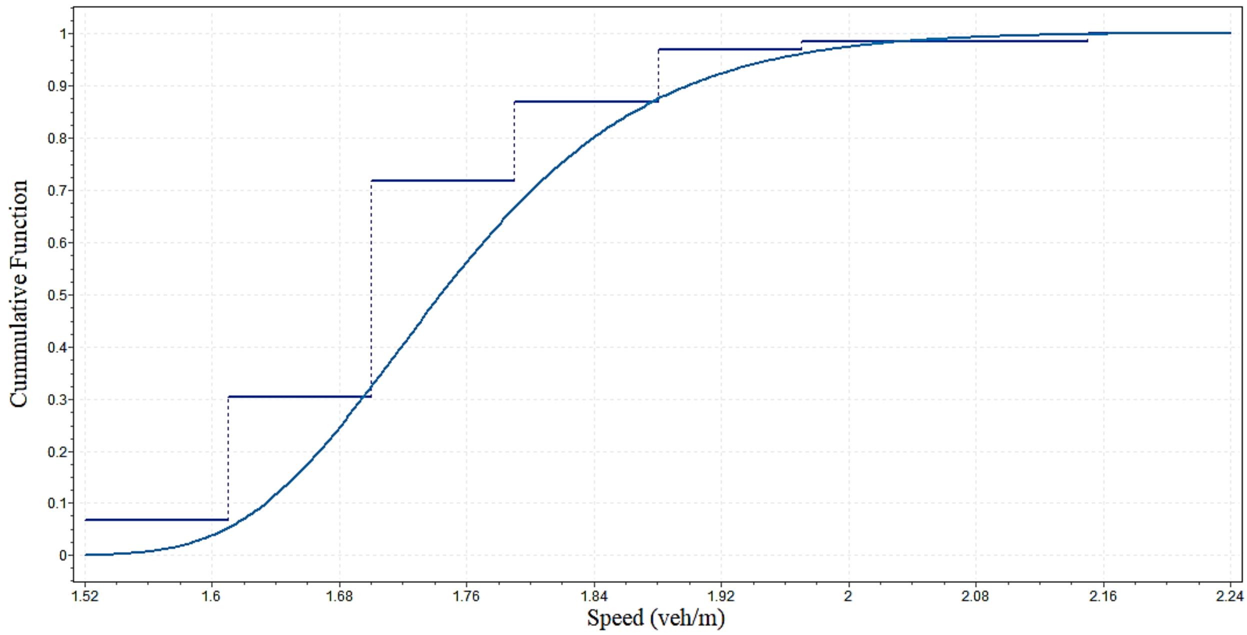

Figure 15. CDF of speed in the afternoon

Binomial distribution is considered best fit for density as it is a discrete variable having a particular outcome. The bin size is 1 veh/m. The probability of 17 veh/m in the morning and afternoon is 0.22 respectively as shown in Figures 10 and 11. The probability of 16 veh/m in the morning is 0.16 as shown in Figure 10, while in the afternoon, it is 0.14 for 16 veh/m, as shown in Figure 11. For 18 veh/m in the morning probability is 0.2 as given in Figure 10. In the afternoon, the probability of 18 veh/m is 0.18. This study is important to evaluate the density behavior throughout survey as it can be used in simulation models [39-41]. The stochastic fundamental diagram is based on speed-density data [42]. Traffic density data is important to indicate traffic congestion and presents the current status of traffic [43].

The cumulative function of density indicates the proportion probability of specific density. Cumulative function in Figures 12 and 13 show the summation of probability mass function of density occurrence. The 75th percentile called third quartile and it comprised 75 percent density data. Figure 12 shows that 0th, 25th, 50th, 75th, and 100th percentile of density in the morning 13 veh/m, 16 veh/m, 17 veh/m, 18 veh/m, and 22 veh /m, respectively. While in the afternoon the 0th percentile is 11 veh/m, 25th is 16 veh/m, 50th is 17 veh/m, 75th is 18, and 100th is 22 veh/m, respectively as shown in Figure 13. The percentile value of density in morning and afternoon are almost similar as both are representing peak hours traffic where minimum and maximum density are 11 veh/m and 21 veh/m, respectively.

The best fit distribution of the target lane speed in morning and afternoon as per KS statistics and p-value is generalized extreme value. This distribution is defined by three main parameters that is scale, location, and shape parameters. The speed values are skewed towards right to its' maximum value of 2.34 m/s. The single bin range of PDF plots is 0.8 with average value of 1.76 m/s in morning and afternoon as shown in Figures 16 and 17.

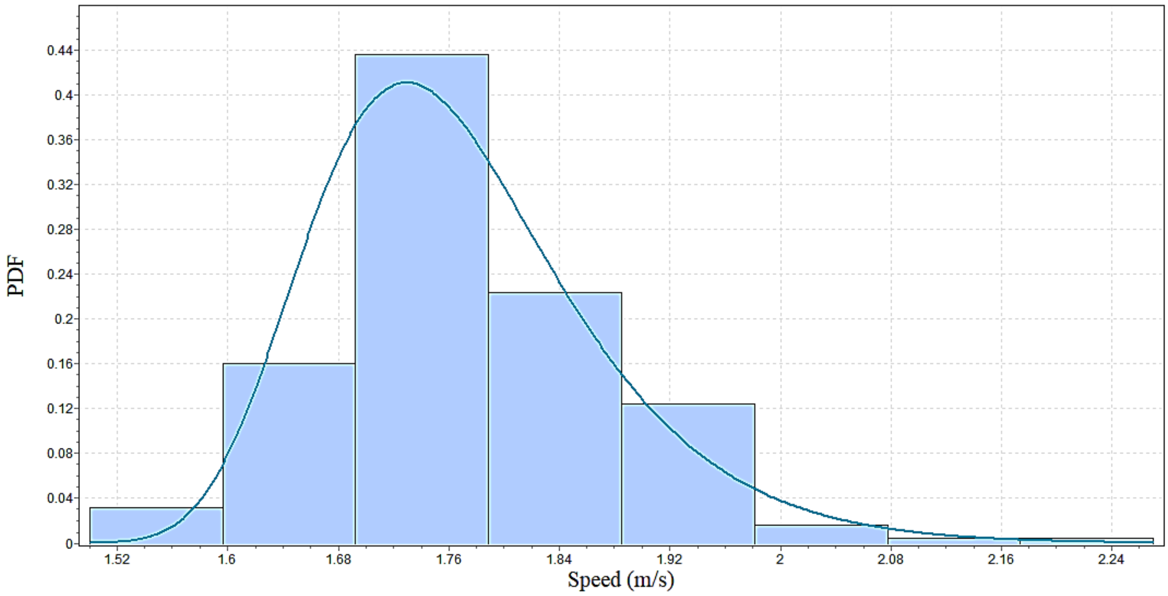

Figure 16. PDF of speed in the morning

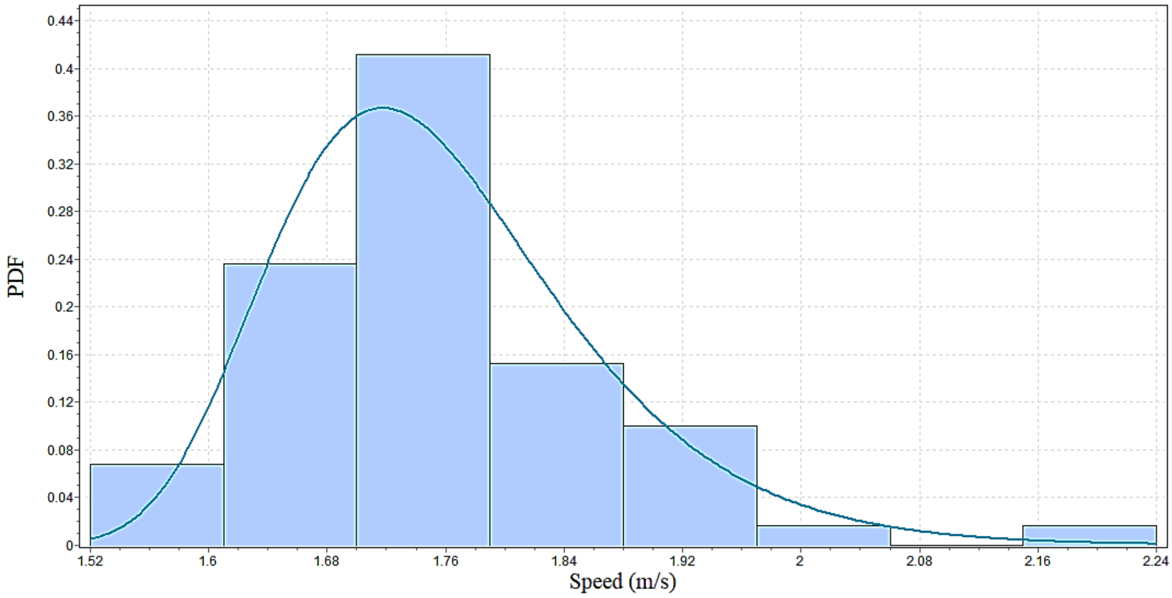

Figure 17. PDF of speed in the afternoon

The cumulative function of speed indicates the proportion probability of specific speed. Cumulative function in Figures 16 and 17 show the summation of probability density occurrence. The 75th percentile called third quartile and it comprised 75 percent speed. The 0th, 25th, 50th, 75th, and 100th percentile of speed in the morning are 1.50 m/s, 1.71 m/s, 1.75 m/s, 1.80 m/s, and 2.27 m/s, respectively. The 0th, 25th, 50th, 75th, and 100th percentile of speed in the afternoon are 1.51 m/s, 1.69 m/s, 1.74 m/s, 1.80 m/s, and 2.23 m/s, respectively. The percentile value of speed in morning and afternoon are almost similar as both are representing peak hours traffic where minimum and maximum speed are 1.50 m/s and 2.23 m/s.

Statistical analysis shows that during morning and afternoon traffic peaks, each vehicle required almost 60.00 s to cover 100 m. However, in off traffic peak time, the travel time through the stationary bottleneck at Arbab Road Peshawar is 11.43 s in the morning. While in the afternoon, the delay is 8.00 s. The increase in delay is due to the stationary traffic bottleneck that occurs due to the newly constructed BRT infrastructure in Peshawar, KPK, at 34.004735 N and 71.053731 E. As result 45 s delay is noticed. The travel delay parameters at stationary bottlenecks are well explained in Equation 7. Target lane density and speed are the main influencing parameters at a stationary bottleneck. The density of a target lane increased due to the breakdown of traffic flow. Consequently, speed is reduced and travel time is increased. Density follows the binomial distribution, while speed follows generalized extreme value distributions. The highest frequencies of density and speed are 17 veh/m and 1.76 m/s, respectively. The maximum and minimum density and speed that correspond to 1 and 0 CDF are 17 veh/m, and 2.24 m/s, respectively. And the minimum density and speed that correspond to 1 and 0 CDF are 11 veh/m, and 1.50 m/s, respectively. It is noteworthy that during the construction of new traffic infrastructure, it is imperative to plan an optimized flow for all types of traffic. Conversely, the improvement in mobility of one type of traffic should not come at the expense of another type of traffic. This increases congestion, delays, pollution, and fuel costs. This also jeopardizes public safety and increases the stress level of the public. It is also difficult for the ambulance and police services to respond to an event on time.

In this paper, the distributions obtained from data at stationary bottlenecks can be employed to characterize realistic and accurate microscopic traffic at the individual vehicle level and macroscopic traffic at the aggregate level. This will help in traffic prediction, congestion mitigation, pollution reduction, improved public safety, fuel cost and efficient utilization of infrastructure.

5. Conclusion

Stationary bottlenecks are a major source of travel time delays. A travel time model was proposed that considers the time taken by a vehicle to find an acceptable gap and then move to the target lane. The time required to attain equilibrium flow after a vehicle enters the target lane and the effect of pedestrians were also examined. The observed time delay during morning and afternoon traffic peak periods was compared with off-peak periods and the ideal case. The parameters for the proposed travel time were obtained experimentally at a traffic bottleneck over a 100-meter road section. It was observed that the target lane density and speed significantly influence the time delay after a successful lane change.

The results obtained show that the average traffic density is 17 veh/m, with a maximum of 22 veh/m. This can result in a delay of almost 45 seconds compared to the off peak period. The mean travel time in the morning and afternoon peak periods is 56.74 and 57.73 seconds, respectively, while in off-peak periods and smooth flow it is 11.34 and 8 seconds, respectively. The density and travel time have a positive linear relationship, while the density and speed have an inverse linear relationship. A higher density increases the time delay and reduces speed. The Kolmogorov-Smirnov (KS) test and P-values were used to identify the best-fit distributions for speed and density, which are binomial and generalized extreme values, respectively. The proposed travel time delay model can provide insight for traffic planners to develop strategies for the infrastructure and predict bottlenecks. Future work can consider traffic data at bottlenecks in other conditions, such as at night or in inclement weather.

6. Declarations

6.1. Author Contributions

Conceptualization, I.B.; methodology, I.B.; formal analysis, I.B., Z.H.K., T.A.G., and K.S.K.; resources, Z.H.K., and T.A.G.; writing—original draft preparation, I.B.; writing—review and editing, Z.H.K, T.A.G, and S.S.; supervision, Z.H.K, and T.A.G.; funding acquisition, T.A.G. All authors have read and agreed to the published version of the manuscript.

6.2. Data Availability Statement

The data presented in this study are available on request from the corresponding author.

6.3. Funding

The authors received no financial support for the research, authorship, and/or publication of this article.

6.4. Conflicts of Interest

The authors declare no conflict of interest.

7. References

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