SIGNAL COORDINATION BASED ON DISTRIBUTION OF PLATOON VARIABLES

A Thesis

by

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ABSTRACT

The traditional method of signal coordination is only based on the average speed of platoon vehicles. This method fails to consider the actual characteristics of the platoon and therefore may not yield optimum coordination results. The characteristics of the platoon is reflected by platoon variables, such as headways or vehicle speeds. In order to take the true characteristics of the platoon into account, a new method that considers the distribution of the platoon variables is proposed in this paper. First, actual traffic data are collected. Distribution studies are conducted based on these data and then compared with normal distribution. The generalized extreme value distribution is found to better fit the platoon data, particularly at both ends. New offset strategies based on different distribution characteristics from the generalized extreme value distribution are then proposed and used as input of simulation for evaluation along with other offset strategies. The optimum strategy is decided based on the simulation results from CORSIM. The results suggest that the optimum offset strategy should be adjusted based on different factors including link length, degree of saturation and cross street volume. It is also found that the optimal offsets correspond to different distribution percentile values for different conditions.

ACKNOWLEDGEMENTS

I would like to thank my committee chair, Dr. Zhang, and my committee members, Dr. Cline, Dr. Lord, for their guidance and support throughout the course of this research.

Thanks also go to my friends and colleagues and the department faculty and staff for making my time at Texas A&M University a great experience.

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1. INTRODUCTION

1.1 Background

For most major arterials, a series of intersections are often closely spaced to each other. In this case, signal timing coordination is required to let the vehicles pass the intersection series rapidly and efficiently. The main goal of signal coordination is to make the greatest number of vehicles pass through the signal intersection while reducing the number of vehicle stops to the lowest. Good signal coordination can effectively reduce the number of stops and delay, and improve the level of service. Determining offset value is critical when performing signal coordination on an arteria corridor. Offset is the difference in time between the between the start of through green of adjacent intersections. Vehicles often arrive to an intersection in “platoons”. Hence it is important to develop a signal timing plan based on the characteristics of these platoons. Platoon characteristics can be reflected by different platoon variables. Though the vehicles in the platoon are mostly closely packed, the speed of vehicles in a platoon still varies. The average platoon speed may not best represent every vehicle in the platoon. Hence signal Coordination based on this single value may not reflect the real-world condition. It is desirable to take other variables into consideration.

1.2 Problem Statement

When performing signal timing coordination, the traditional methods use a single value of speed to calculate offset. The speed used is often the average speed of the platoon. The real situation, on the other hand, is that the vehicles in a platoon may have different speeds. A single value of speed may not be representative of all the vehicles in the platoon and signal coordination based on this may not give the best solution. Hence, it would be desirable to consider the parameters that represents the platoon characteristics comprehensively. The objective of this proposed thesis work is to study the headway and speed distribution of the platoon and their influence on the offset. Based on this, possible methods to input the speed distribution parameters into the signal coordination process will then be investigated and simulation will be conducted to verify if the revised signal timing strategy based on the new speed distribution performs better than the traditional method. First, the speed and headway data in a platoon will be collected. The data collection includes collecting speeds at different locations along a link, such as the upstream, midsection, and downstream. Then possible distribution types can be determined with these data. Different values of offsets will be obtained from different input speeds which are based on the distribution type. The offsets will then be simulated using traffic simulation software like CORSIM to evaluate their performances. The simulation result will be used as the reference of developing a set of optimal offset strategy.

1.3 Research Significance

Though a lot of research work have been done on both fields of platoon dispersion and signal coordination strategies, few studies were able to link them together. This research is conducted on the motivation of finding a more appropriate distribution type for the platoon variables and developing a coordination strategy that is able to take full consideration of platoon characteristics. The new strategy based on platoon distribution is supposed to be more representative of the real-world condition than the traditional method. If simulation results validates that the new strategy is better than the traditional one, this strategy can be adopted to improve the arterial's overall performance. Moreover, platoon variable distribution can be better understood through actual data collection.

1.4 Research Objectives

The goal of this research is to develop a new offset strategy based on the distribution of platoon variables. The research objectives are:

- To identify key platoon variables and study their distribution pattern based on traffic data.
- To verify if the proposed distribution out-performs the commonly assumed normal distribution.

- To develop a new offset strategy based on distributions.
- To validate if the developed strategy out-performs the traditional strategy.

2. LITERATURE REVIEW

2.1 Previous Research on Platoon Variable Distributions

A considerable portion of research has been focused on the study of platoons on arterials. The most important platoon variables are the platoon size, time headway and travel speed (1, 2, 3, 4, 5, 6, 7). Studies confirmed that the headway threshold for the interaction between successive vehicles in a platoon is about 5-7 seconds (2). It was also found that very short headways such as those less than 1 second were mostly related to aggressive driving with high speeds.

A few studies focused on the platoon variable of time headway. A paper by Wei et al. (7) studied the platoon dispersion model assuming that the platoon speeds had a truncated normal distribution. Platoon dispersion is one reason that makes signal coordination complicated. The most commonly used approach in platoon dispersion study is Pacey's diffusion theory. Pacey described platoon diffusion using a kinematic model based on the assumption that travel speeds follow a normal distribution. The limitation of this model is that is only applies to traffic cycles with minor changes. Wei et al (7) improved Pacey's assumption on normal distribution which ranges from negative infinity to positive infinity, by proposing a truncated normal distribution which only ranges from a minimum speed to a maximum speed. A piecewise density function was used to calculate the expected number of cars that passes or do not passes a downstream intersection. Then dispersion models were developed to facilitate traffic signal control system coordination. The key is to design for the front and rear of platoons using Pacey's assumptions. The author considered the scenarios of cars at front that have passed the downstream intersection and the cars at rear that have not passed the downstream intersection. Four parameters were used to calibrate the model: the average speed, the standard deviation of speeds the minimum and the maximum speeds.

Signal coordination optimization programs like TRANSYT use a recurrent dispersion model developed by Robertson. The model was based on a shifted geometric distribution of travel time. This may not be the real situation as proved by many later researches (8, 9) that the travel time distribution are more consistent associated with a normal or lognormal distribution. An improvement on Robertson’s model as by Wu et al. (9) considering bus traffic. The study proposed a macroscopic mixed platoon flow dispersion model to simulate platoon dispersion process between two intersections. The author used a truncated Gaussian mixture distribution to describe the flow-density relationship. Then between arriving and departing flow distribution can be investigated. Compared to Robertson’s model, the mixed platoon flow dispersion model was able to include different types of vehicles.

The headway or spacing distribution can also be represented by a Markov model (10) which links mesoscopic headway distribution model and microscopic vehicle interaction model. Model parameters were estimated based on Next Generation Simulation Trajectory Data. The model development was further aided with the break-down of driving scenarios (free driving, starting, breaking and following mode) and psychological explanations. As a result, the Markov model was proved to describe the headway distribution better as a psychological car-following model.

Research efforts have also been put into the area of departure headway study. A paper by Jin et al. (11) aimed to propose a car-following model that was able to explain the departure headway distribution, which from the authors’ findings, followed a lognormal distribution. This result was obtained by analyzing each position individually. Three modes with distinct behavior were included in the proposed car-following model: stopped mode, starting-up mode and driving/braking mode. Besides headway, other variables such as start-up lost time and effective departure flow rate also attract the attention of researchers. Tan et al. (12) aimed to develop distribution model for the two mentioned variables according to their relationship with departure headway distribution. Their study showed that the start-up lost time followed a lognormal distribution and the effective departure flow rate had a discrete and a continuous distribution.

It is common to see the platoon dispersion phenomenon on major urban arterial roads, as vehicles are released by the upstream traffic signal. Hence the arrival pattern of at downstream intersection is highly influenced by the platoon dispersion (13). However, compared to other traffic parameters, platoon dispersion is hard to determine. A study by Mashros et al. investigates platoon dispersion caused by traffic signals on arterials (14). Vehicle headway, intra-platoon headway and inter-platoon headway are studied by videotaping field data in Malaysia. These data were then fitted with distribution models and it is found that the vehicle headway has Erlang and shifted negative exponential while intra-platoon headway has normal distribution. Inter-platoon headway on the other hand, does not follow any distribution tested.

Another study on platoon dispersion is about its characteristics under heterogeneous conditions (15). The study also used videotaping equipment to collect data in India. Since the traffic in India is highly heterogeneous, the Robertson's model parameters were highly distinctive for these data. The study attributed the highly dispersed traffic to the mix of different vehicle types travelling at different speeds, and pointed out that each type should be studied separately. A similar study was done by Arasan and Kashani (16). They aim to study the arrival type of traffic streams as well as queue accumulation and dissipation by developing a simulation technique that is able to model heterogeneous traffic flow. Their technique treat a segment of road as a matrix consisting many small cells, and treat vehicles as moving rectangular blocks. Mixed traffic flow is able to be simulated in this way.

2.2 Different Bandwidth Optimization Strategies

By far, a large amount of research efforts have been put into the study of bandwidth optimization of and many methods have been proposed, taking different aspect of considerations into account. Wu et al. (17) managed to solve the optimization problem with a group partition method. They calculated upper and lower interferences and relative offset, and used a Windows program to draw the time-space diagram for an arterial. The arterial was partitioned into several subgroups and optimal bandwidth is obtained for every subgroup. The phase sequence and offset can also be obtained for every subgroup, after calculating the optimal progression bandwidth. Bandwidth optimization considering minor cross roads is another interesting topic.

Jiang et al. (18) identified four key variables to represent platoon characteristics mathematically: platoon size, platoon headway, platoon speed and inter-arrival time. They found that each variable has a distinct distribution. The platoon size has a negative exponential distribution while the inter-arrival time has a lognormal distribution. Both the headway and the speed has normal distributions. The distributions were then used in the platoon-based signal timing algorithm aiming at minimizing the interruptions on the major road and reducing the delay at the minor road to an acceptable level at them same time.

In practice, link bandwidth should also be taken into consideration, since not all drivers pass through all the intersections in an arterial. In their paper, Wu et al. (19) presented the bandwidth optimization algorithm that balance between link bandwidth and arterial bandwidth by considering vehicle speeds. The authors improved Messer's algorithm which has limitation in arterials with high number of intersections. Their result showed that the MOEs including bandwidth efficiency and attainability were much improved.

2.3 Other Relevant Studies on Platoon and Signal Coordination

Platoon dispersion can be caused by many reasons, such as traffic signal, road geometry, and some other factors. The Highway Capacity Manual (HCM) states that many factors influence how fast a platoon disperses (20). Vehicle's travel speed and traffic volume are the two main reasons. It has been proved that the number of lanes will highly affect the platoon dispersion characteristics (21). Bie et al. used the Robertson's model for the platoon dispersion and recalibrate the platoon dispersion factor based on the road data collected in China. The data were collected from segments with two to five lanes. The result showed that the platoon dispersion factor has dropped significantly as the number of lanes increases from two to five.

Another study on urban street platoon dispersion relate it with internal and external frictions (22). Manar and Baass states that platoon dispersion will increase as volume and density increases, and will reach its maximum at about half of the capacity. Then the dispersion will go down and attains its minimum at maximum capacity. Their study was based on data collected near Montreal before and during peak hours. A parabolic model is proposed to relate traffic volume and platoon dispersion factor. It is concluded that the influence of external factors, including parking, turning movements, pedestrians and geometric elements, are as important as internal factors on platoon dispersion factor.

The effect of turning movement is further studied by Bie et al, aiming to calibrate the Robertson's dispersion parameter. They divide the link into two sections: road section and channelized section and collected data accordingly to study how the dispersion parameter are influenced by factors such as traffic volume and turning proportion. Finally they were able to establish relationship models between the variables for the road section and channelized section.

3. DATA COLLECTION

3.1 Data Collection

To study the actual distribution of the speed and headway of platoon vehicles, local data were collected. These data were collected on Texas Avenue, College Station, Texas, as shown in Figure 1. To avoid over-saturated conditions, the data were collected during non-peak hours of weekdays. The actual data collected were vehicle headway and the vehicles' travel time on a link of a certain length. Four data collection locations were selected to study platoon variables distribution over different link lengths. They were at the upstream, midsection, downstream and further downstream locations of the link, having distances of 620 feet, 1200 feet, 1870 feet and 2370 feet from the upstream intersection. The downstream intersection however, is actually located between the downstream (1870 feet) location and the further downstream (2370 feet) location. Since it can be observed that the signals were coordinated well between these two intersections and that platoons can pass though these two intersection without reducing their speeds, the effect of the downstream intersection can be neglected and the measure time is the actual travel time for 2370 feet link.

Previous studies on speeds were mainly spot speed studies (7, 9, 11 and 25), meaning collecting vehicle speeds at a point. This study however, obtains speed data by collecting vehicles' travel time over an extended link length. The travel time data is converted into speed data and represents the vehicles' travel speeds over the entire link.

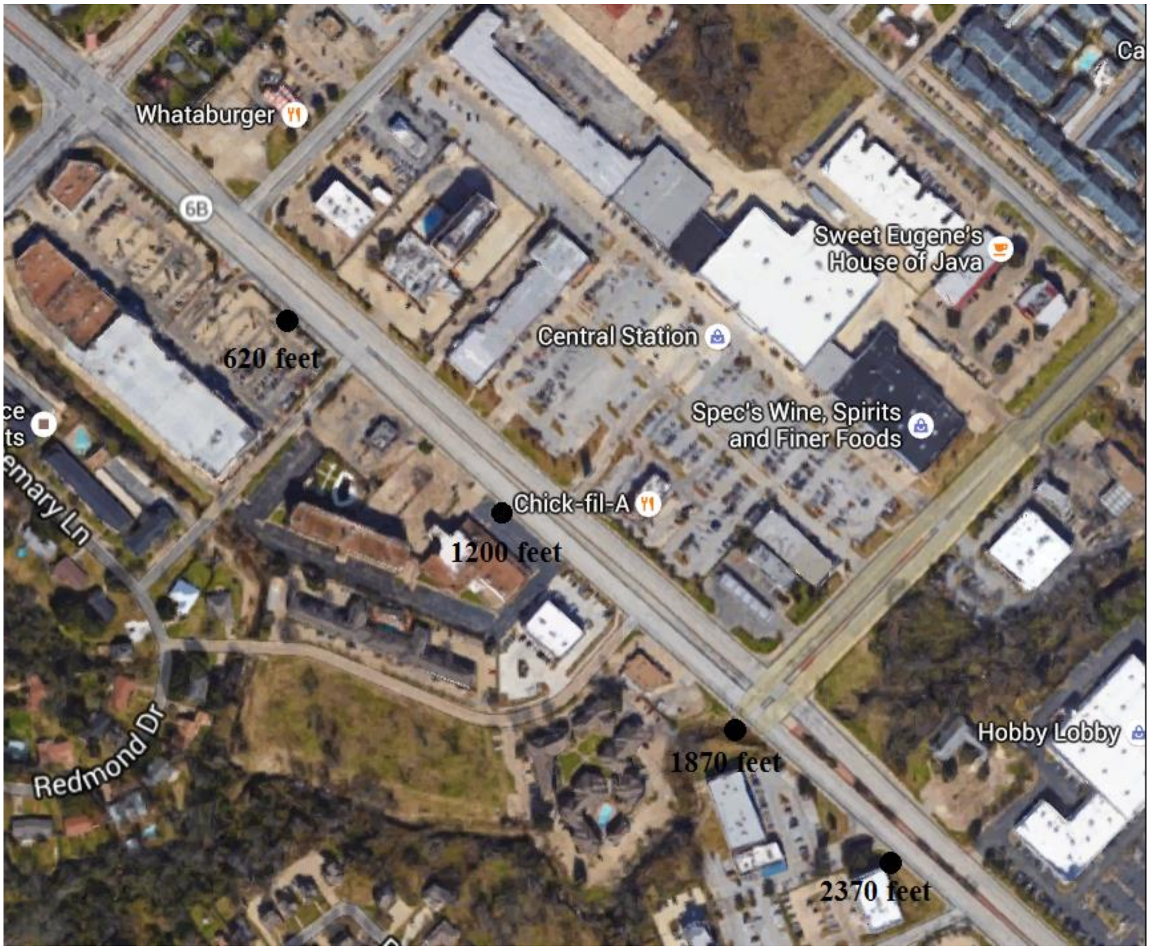

Figure 1. Data Collection Locations

3.1.1 Headway Data

Headway data were collected from each point along the link. 750 headway data were collected at the 1200 feet location. About 200 data were collected at the other three locations. The data were collected manually with a simple timing software that is able to take records of multiple time counts. From the first vehicle to the last vehicle in the platoon, the arrival times is recorded and the differences between these arrival times were automatically calculated by the software. These differences in time were the headway of vehicles in the platoon.

3.1.2 Travel Time Data

Travel time data were also collected in order to calculate the speeds of the vehicles. The travel time is the approximate time the leading vehicle takes to travel from the upstream intersection to the data collection point. About 200 travel time data were collected four each of the four points. The data were also collected manually using the mentioned software. These travel time data will then divide their respective distance from the upstream intersection to obtain the travel speeds of the vehicles.

During the travel time data collection process, it was observed that the a few vehicles tended to be travelling much faster than the majority of the vehicles. Since they were ahead of the platoon and arrived much earlier, they were not considered to be in the platoon. As mentioned previously, the inter-arrival time between these vehicles and others were much larger than the effective headway for platoon interaction (5-7 seconds). The travel time data for these vehicles were not recorded. The real platoon followed these vehicles and the travel time of the first vehicle was recorded.

3.2 Data Presentation

3.2.1 Headway Data

The headway data are divided into 4 categories according to their locations: 620 feet, 1200 feet, 1870 feet and 2370 feet. Their statistical parameters are calculated and presented in the following table, Table 1.

Table 1. Descriptive Statistics for Headway Data

Description Statistics	620ft	1200ft	1870ft	2370ft
Sample Size	206	750	204	209
Mean	2.935	2.377	2.778	2.929
Variance	0.484	0.452	0.555	0.974
Standard Deviation	0.695	0.672	0.745	0.987
Max	4.485	4.560	4.974	4.992
Min	0.992	1.009	0.899	0.772
Range	3.493	3.551	4.075	4.220
Median	2.868	2.386	2.691	2.997

A general pattern of increasing variance, standard deviation and range can be observed from the data, as the distance increases. This pattern corresponds to the theory of platoon dispersion which states that platoons disperse over time and space. At upstream locations where travel distance is relatively short, vehicles are more closely packed in the platoon. This is reflected by the lower variance and range of headway. At downstream locations where travel distance is relatively long, the platoon seem to be more dispersed, as there are longer range of headways. The upper and lower bounds of headway values increases as distance becomes longer.

From the table, it can be seen that the data collected at the 1200 feet point actually have smaller variance and standard deviation than the data collected at the 620 feet point. This may be caused by the larger sample size (750 vs. 200) collected by the 1200 feet. Increasing the sample size may result in lower variances, thus yielding the result shown in the table above.

3.2.2 Travel Time Data and Speed Data

Like the headway data, the travel time data are also divided into 4 categories according to their locations: 620 feet, 1200 feet, 1870 feet and 2370 feet. Their statistical parameters are calculated and presented in the following table, Table 2.

Table 2. Descriptive Statistics for Travel Time Data

Description Statistics	620ft	1200ft	1870ft	2370ft
Sample Size	200	200	200	200
Mean	13.520	22.987	30.579	39.051
Variance	0.697	1.749	4.200	7.941
Standard Deviation	0.835	1.323	2.049	2.818
Max	14.997	26.990	36.089	45.934
Min	12.009	20.163	26.050	32.047
Range	2.988	6.827	10.039	13.887
Median	13.530	22.702	30.656	39.322

The dispersion of platoons can also be observed from the travel time data. With same sample size for every data collection point, a clear pattern on the variance and range can be observed. As the distance increases, the variance increases from 0.697 mph to 7.941 mph. The range increases from 2.988 mph to 13.887 mph. This means vehicles in a platoon use similar time to travel a small distance, while takes diverse time to travel longer distances. Comparing to headway data, the variance and range differs significantly from one another. For a distance of 620 feet, the difference in travel time between the fastest and the slowest vehicle is only about 3 seconds, as they can pass in 12-15 seconds. However, for a distance of 2370 feet, the fastest vehicle only takes 32 seconds and the slowest takes as long as 46 seconds to pass. The different in travel time increases to 14 seconds. This shows that the platoon is more dispersed at downstream locations than upstream locations.

The travel time data are then used to calculate the speeds of the vehicles, by dividing their corresponding travel distance. The summary statistics for the resulted speeds are presented in the following table, Table 3.

Table 3. Descriptive Statistics for Speed Data

Description Statistics	620 feet	1200 feet	1870 feet	2370 feet
Sample Size	200	200	200	200
Mean	31.387	35.707	41.882	41.602
Variance	3.820	3.905	7.962	9.669
Standard Deviation	1.954	1.976	2.822	3.109
Max	35.201	40.578	48.944	50.423
Min	28.187	30.314	35.329	35.179
Range	7.013	10.264	13.615	15.244
Median	31.244	36.041	41.591	41.095

The speed table shows a clearer view of platoon dispersion. The difference in variance and range is significant. Drivers are likely to increase their travelling speeds as distances increases. From the shortest distance to the longest distance, the maximum speed increases to 50mph and the minimum speed increases to 35 mph. At short distance, the vehicle speeds have a lower range, 7.013 mph. The range value increases to 10, 13 and 15 miles per hour. This shows that the difference in vehicle gradually increases as their travel distance gets longer. As the speed range gets larger, the platoon length also gets longer.

From the data collected, a clear phenomenon of platoon dispersion can be seen. Both the headway and the speed differs more significantly as the distance increases. This will cause difficulty in signal coordination. The solution to this problem will be further investigated in the following part of the thesis.

4. DISTRIBUTION STUDY

As mentioned previously, platoons have significantly dispersed as vehicles travel downstream. There are more variations of headway and travel time/speeds. This will bring difficulties to signal coordination. If the traditional method, using the average speed to calculate offset, is still used, the coordination result may not be an optimal one. Hence it is important to study the distribution of these platoon variables and find out if there are any better replacements for the average value.

The distribution study is aided with two statistic software, JMP and EasyFit. JMP (28) is a more well-known software from SAS and is used as the primary analysis software. EasyFit is a supplemental software to JMP and was brought in when none of the distributions in JMP fits well with the data. It provides more distribution types and additional test methods to aid the distribution fitting process.

4.1 Headway Distribution

For headway distribution, some of the most possible distributions are selected first. They are then tested with two test methods: Kolmogorov-Smirnov test, and Anderson-Darling test too make a comprehensive comparison. The Shapiro-Wilk test is also conducted on normal distribution. A table, Table 4, with corresponding test statistics is used to aid distribution fitting. It is easy to tell from the table that which distribution has the most best-fits.

Table 4. Goodness-of-fit Test Statistics of Headway Data

Headway				
	620 feet	1200 feet	1870 feet	2370 feet
Normal				
SW	0.977657	0.988491	0.984194	0.985963
KS	0.07921	0.02768	0.06649	0.03909
AD	1.7205	1.0614	1.0413	0.43922
Weibull				
KS	0.08854	0.03552	0.07266	0.04885
AD	2.7543	1.7806	1.5947	0.63238
Lognormal				
KS	0.057114	0.070155	0.066031	0.11251
AD	0.91838	6.0999	1.4947	4.5049
3P Gamma				
KS	0.06791	0.0371	0.05312	0.05935
AD	1.2448	1.564	0.65519	0.82563
Extreme Value				
KS	0.056	0.02673	0.04916	0.02978
AD	0.91988	1.0801	0.62259	0.34107

Though collected from different locations, the data are from similar situations and they are along the same link. Hence they should be fit into a single type of distribution. From the table, the Extreme Value distribution has lower test statistic than other distributions, for both Kolmogorov-Smirnov test and Anderson-Darling test. Hence the extreme value distribution is selected to be the distribution that fits the headway data.

Here the extreme value distribution refers to the generalized extreme value distribution. The generalized extreme value distribution has the following cumulative distribution function:

$$\mathrm{F}(x;\ \mu, \sigma, \xi)\ =\ \exp\{-[1 + \xi * (\frac{x-\mu}{\sigma})] - 1/\xi\} \qquad (1)$$

Where μ is the location parameter, σ is the scale parameter, and ξ is the shape parameter.

Other statistics like the mean, variance, mode and skewness can also be calculated with the following equations:

Mean:

$$\mathrm{E}(\mathrm{X})\ =\ \mu - \sigma/\xi\ +\ (\sigma/\xi) * g_1 \qquad (2)$$

Variance:

$$\mathrm{Var}(\mathrm{X})\ = (\sigma^2/\xi^2)\ *\ (g_2 - {g_1}^2) \qquad (3)$$

Mode:

$$\mathrm{Mode}(\mathrm{X})\ = \mu\ +\ (\sigma/\xi)\ *\ [(1 + \xi)^{-\xi} - 1] \qquad (4)$$

Skewness:

$$\mathrm{Skewness}(\mathrm{X})\ =\ (-g_3 + 3g_1g_2 - 2{g_1}^3)/(g_2 - {g_1}^2)^{3/2}\ \text{(for } \xi < 0) \qquad (5)$$

Where μ is the location parameter, σ is the scale parameter, and ξ is the shape parameter, and $g_k = \Gamma(1\text{-}k\xi)$, k = 1, 2, 3, 4, and Γ(t) is the gamma function.

The histograms for the data collected from each location is provided for a better understanding of the distribution fit, as shown in Figure 2 to Figure 5.

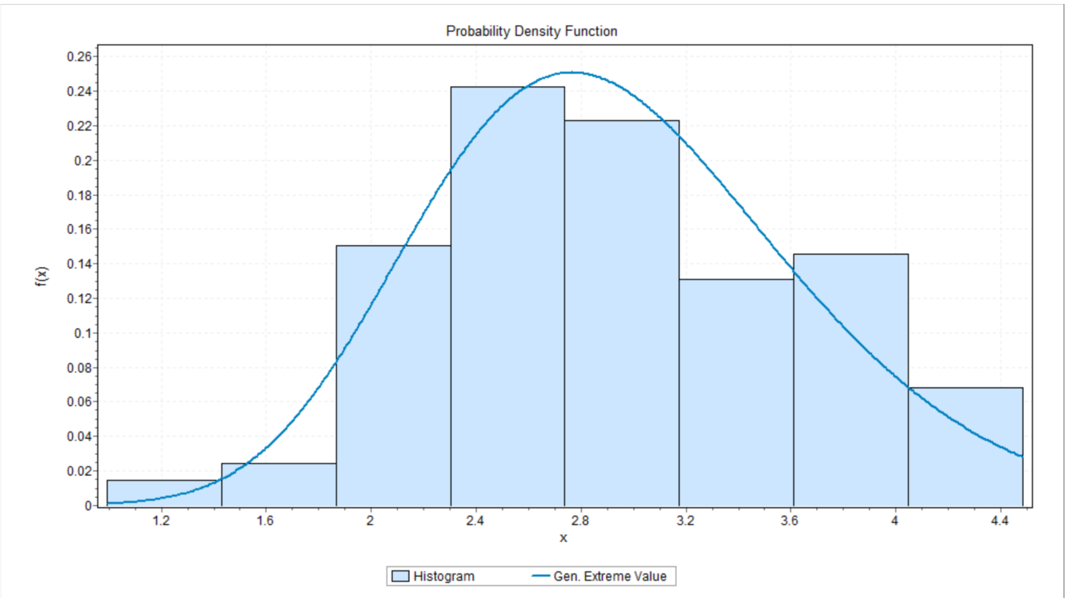

Figure 2. Histogram of Headway at 620 Feet

$\mu = 2.6511$, $\sigma = 0.64930$, $\xi = -0.16194$

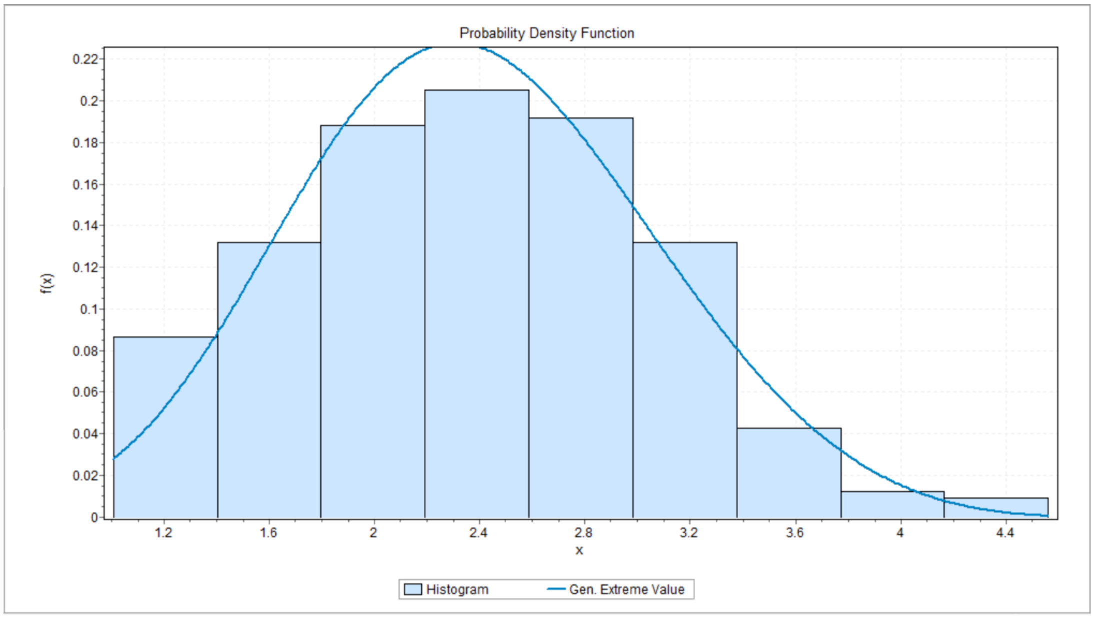

Figure 3. Histogram of Headway at 1200 Feet

$\mu = 2.1282$, $\sigma = 0.65855$, $\xi = -0.24421$

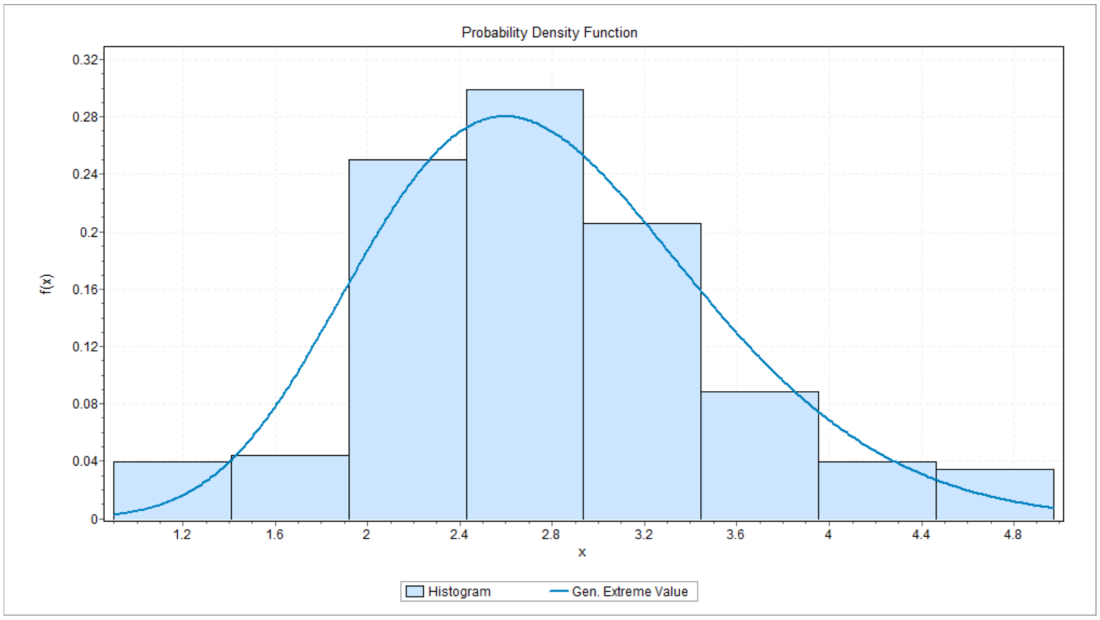

Figure 4. Histogram of Headway at 1870 Feet

μ = 2.4802, σ = 0.67759, ξ = -0.15838

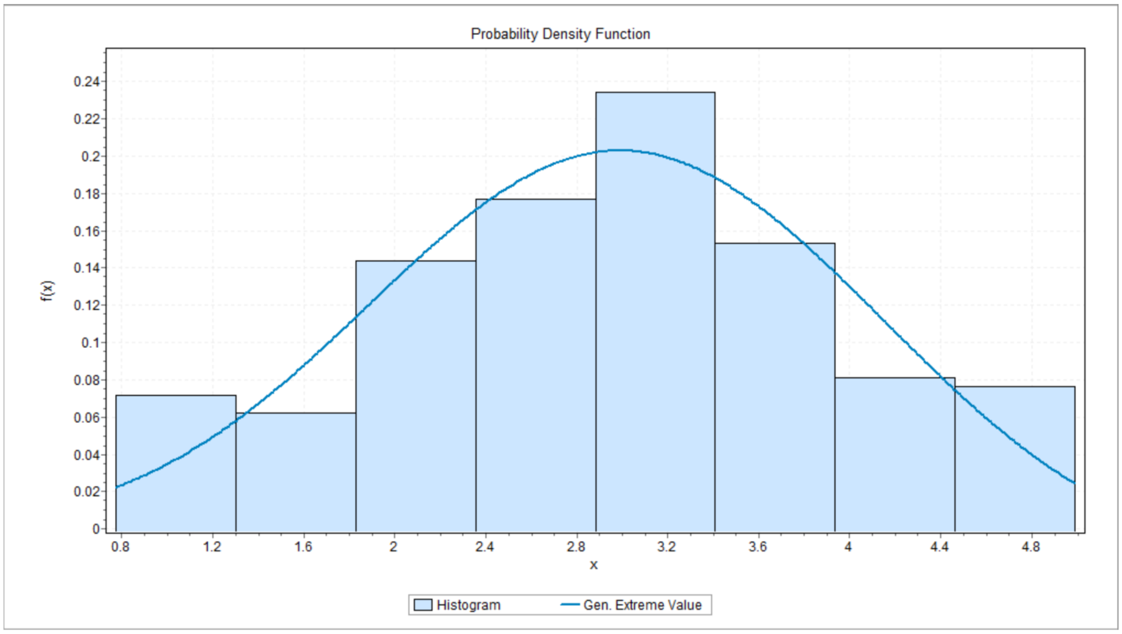

Figure 5. Histogram of Headway at 2370 Feet

μ = 2.6021, σ = 1.0187, ξ = -0.33346

The generalized extreme value distribution is actually a family of continuous distributions including Gumbel, Frechet, and Reversed Weibull distribution. They are also called type I, type II and type III extreme value distribution. They are differentiated based on the value of ξ . When $\xi = 0$, the distribution belongs to Gumbel or type I extreme value distribution, When $\xi > 0$, the distribution belongs to Frechet or type II extreme value distribution. When $\xi < 0$, the distribution is categorized as the reversed Weibull or type III extreme value distribution.

For the above cases, all four shape parameter are less than zero. Hence all four distributions can be categorized into the type III extreme value distribution. Here we are able to use one distribution, the type III extreme value distribution to model the headway of all four locations along the link.

4.2 Travel Time and Speed Distribution

The travel time and speed distribution are discussed together since the speed data are derived from the travel time data. Similar to the headway distribution study, distribution types that could most possibly fit the data are first selected. Then goodness-of-fit tests are conducted on them and the results are grouped into a table for a comprehensive comparison. The goodness-of-fit tests are the Kolmogorov-Smirnov test and the Anderson-Darling test.

For both the travel time and speed data, the optimum distribution is still the generalized extreme value distribution. The results of the goodness-of-fit tests can be found at Appendix Table A-1: Goodness-of-fit Test Results for Travel Time Data and Appendix Table A-2: Goodness-of-fit Test Results for Speed Data.

Figure 6 to Figure 9 are the histograms and fit curve for the travel time data distribution, with their respective location, scale and shape parameters.

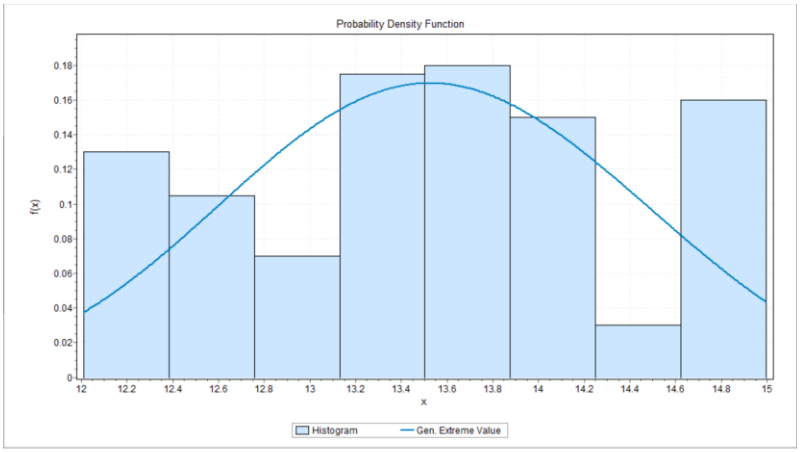

Figure 6. Histogram of Travel Time at 620 Feet
μ = 13.231, σ = 0.85272, ξ = -0.30404

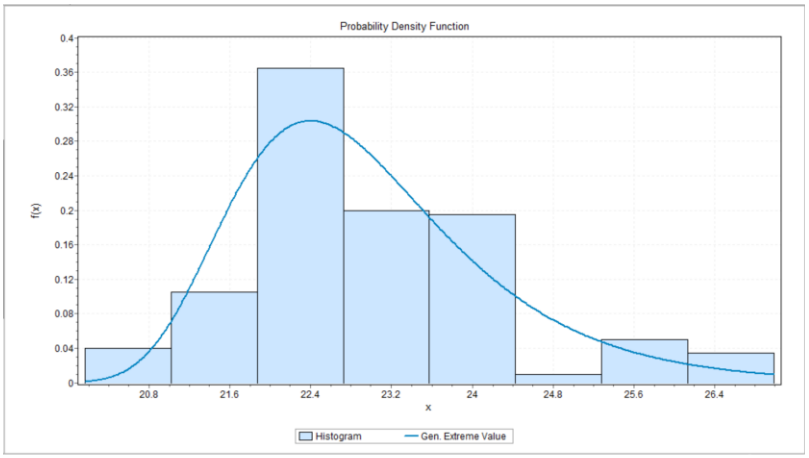

Figure 7. Histogram of Travel Time at 1200 Feet
μ = 22.394, σ = 1.0338, ξ = -0.00391

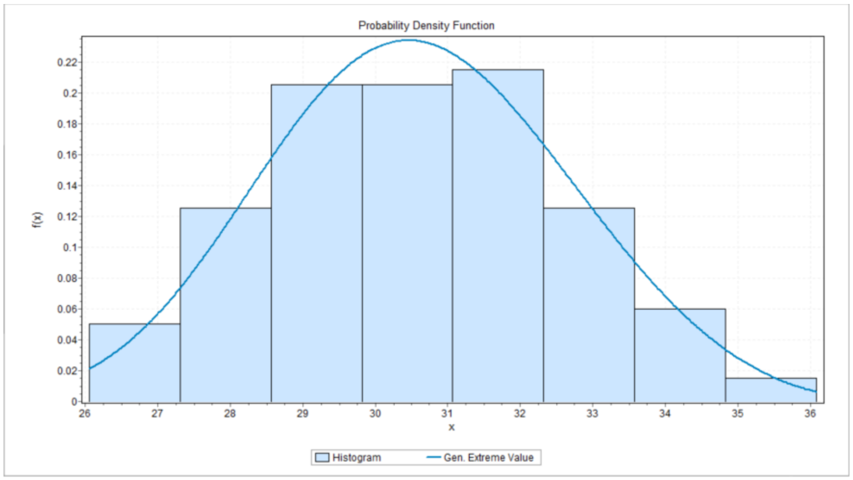

Figure 8. Histogram of Travel Time at 1870 Feet
μ = 29.836, σ = 2.0542, ξ = -0.26889

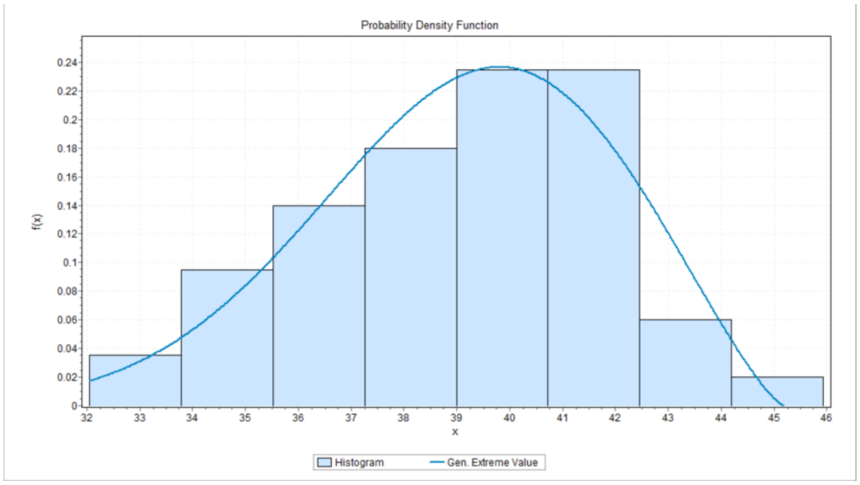

Figure 9. Histogram of Travel Time at 2370 Feet
μ = 38.262, σ = 3.0199, ξ = -0.43661

Similar histograms and fitted curves for speed data are also provided below as Figure 10 to Figure 13.

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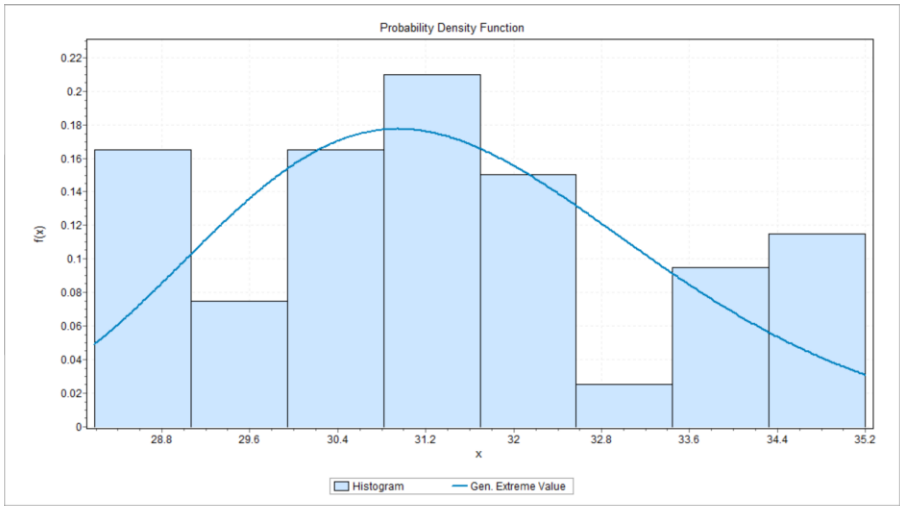

Figure 10. Histogram of Speed at 620 Feet
µ = 30.597, σ = 1.8475, ξ = -0.17492

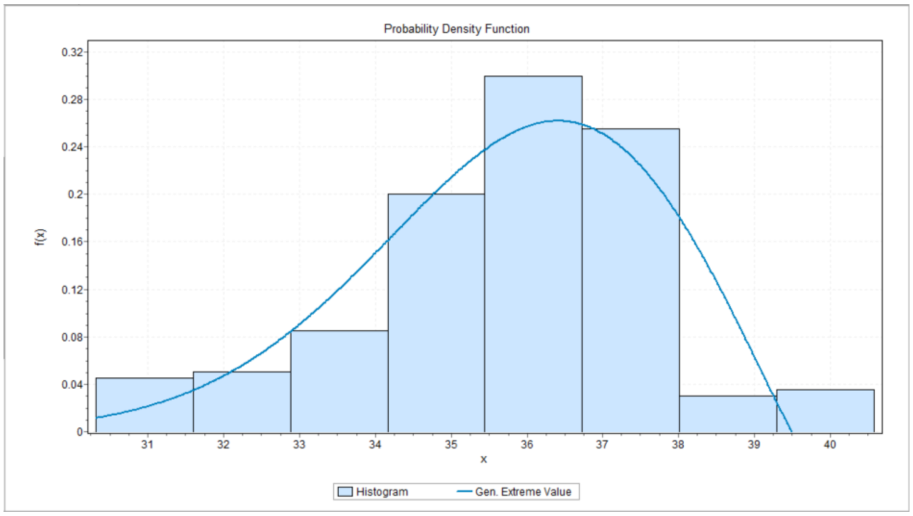

Figure 11. Histogram of Speed at 1200 Feet
µ = 35.219, σ = 2.0826, ξ = -0.48765

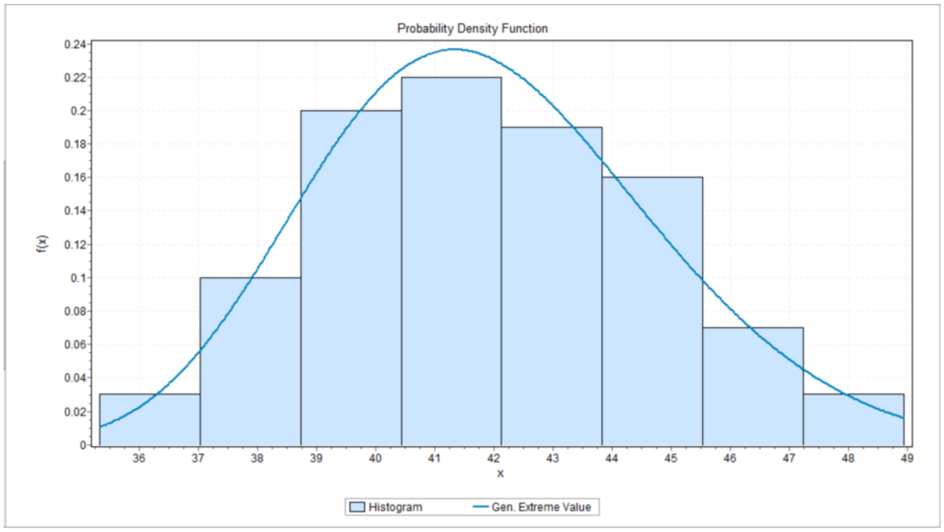

Figure 12. Histogram of Speed at 1870 Feet

$\mu = 40.776$, $\sigma = 2.7020$, $\xi = -0.19426$

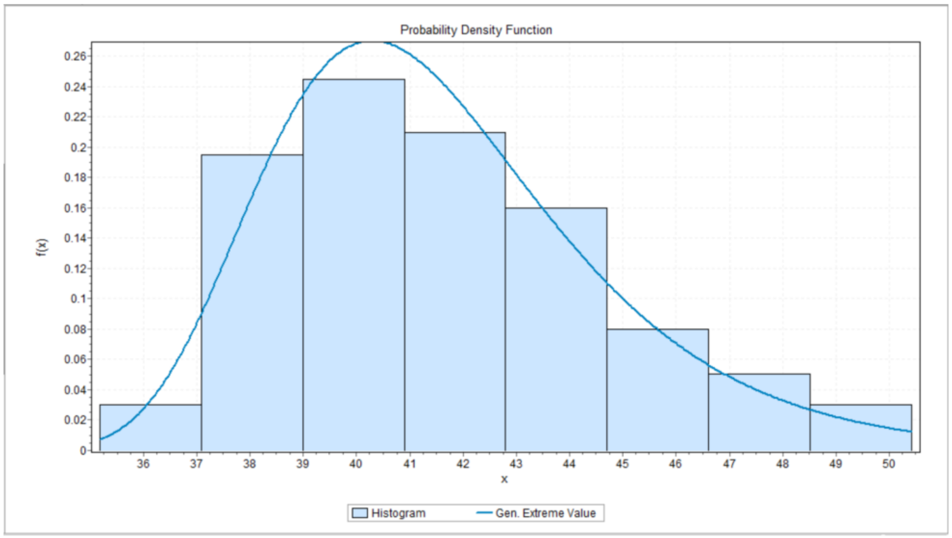

Figure 13. Histogram of Speed at 2370 Feet

$\mu = 40.195$, $\sigma = 2.5958$, $\xi = -0.03687$

It can be seen that for both travel time and speed distribution, the shape parameter is below zero. Hence both the time and speed distribution belongs to the type III extreme value distribution.

For the travel time distribution at 620 feet, the histogram seems to be scattered and not following a good pattern. The same thing happens for the speed distribution at 620 feet, since the speed is calculated from the travel time. This can be expected, since the range of the data at 620 feet is rather small. The data lays only between 12 to15. Setting the bin width to be 1 will only result in 3 columns like Figure 14. This does not provide a good visual aid in distribution fitting. On the other hand, if the bin width is set less than 1, the accuracy of the data cannot be guaranteed since the data are collected manually and it is hard to accurate to 0.1 seconds. Considering the fact that generalized extreme value distribution fit the data for other three locations well, and that the test result does not reject a generalized extreme value distribution at the 620 feet location, the generalized extreme value distribution is selected for all four locations.

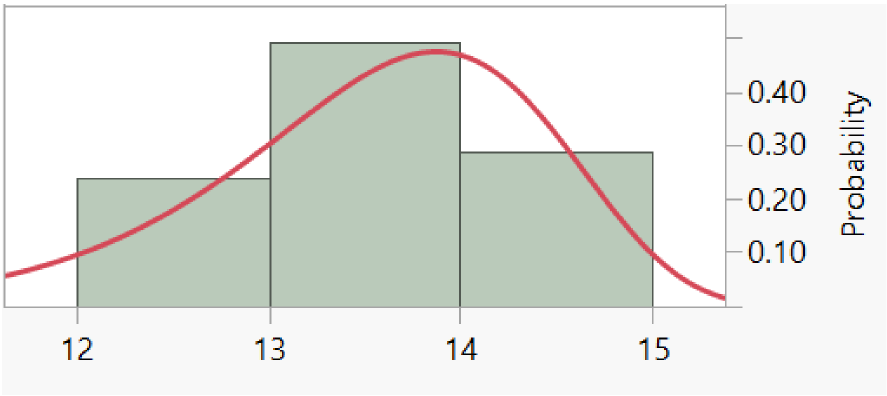

Figure 14. Histogram of Travel Time at 620 Feet with 1 Second Bin Width.

The result for distribution fitting is that the type III extreme value distribution can be fitted into the data collected from each location. The distribution could be used to calculate different parameters that could be used in offset determination. The next step is to select the parameter that yield the optimum offset.

4.3 Comparison with Normal Distribution

Speeds corresponding to various percentiles of the generalized extreme value distribution can be calculated from equation (1). The speed values are then compared with the percentile values calculated from the assumption that the data follows a normal distributions. It can be observed from Table 5 that the central portion of the generalized extreme value distribution and normal distribution is rather similar. This means both the normal distribution and the generalized extreme value distribution are capable of modeling vehicles traveling at a medium speed, which in most cases form the middle of the platoon. The main difference between the two theoretical distributions is at the two tails. Since the generalized extreme value distribution is determined to be type III, it has an upper bound. This corresponds to the observation that very fast vehicles were not considered to be in the platoon and their data were no collected. Since there is also a maximum speed limit for the platoons, the upper tail should be truncated. For the lower tail, greater differences between the two distributions can be observed. This shows that the normal distribution is not able to model the slower vehicles of the platoons well. In addition, it can be observed that the differences in percentile values are more significant for longer links. The difference increases from 1 mph to 3 mph at longer links. This may be explained that there will be more variation of speeds and greater dispersion on longer links. In these cases, the normal distribution will not be able to model the slower vehicles well. Hence it can be concluded that the type III generalized extreme value distribution outperforms the normal distribution with better modelling on the front and rear of the platoon, especially on longer links. This advantage is important, since it is later discovered from the simulation results that the slower vehicles highly influence the offset values. In the later part of the paper, when investigating offset strategies certain percentile values based on the type III generalized extreme value distribution are considered as candidate offset values.

Table 5. Comparison with Normal Distribution (Unit: mph)

	620 feet		1200 feet		1870 feet		2370 feet	
percentiles	Gen. Ex	Std. Norm.	Gen. Ex	Std. Norm.	Gen. Ex	Std. Norm.	Gen. Ex	Std. Norm.
99% percentile	36.435	35.933	39.037	40.304	48.983	48.446	51.178	48.835
95% percentile	34.877	34.601	38.487	38.957	46.863	46.523	47.498	46.716
90% percentile	34.034	33.891	38.065	38.239	45.691	45.498	45.801	35.586
85% percentile	33.472	33.412	37.729	37.755	44.903	44.806	44.757	44.824
75% percentile	32.665	32.705	37.164	37.039	43.756	43.785	43.356	43.699
70% percentile	32.340	32.412	36.907	36.743	43.290	43.362	42.821	43.232
50% percentile	31.253	31.387	36.041	35.707	41.721	41.882	41.140	41.601
4% percentile	28.201	27.965	31.937	32.247	37.219	36.942	37.094	36.158
20% percentile	29.680	29.742	34.104	34.043	39.419	39.507	38.949	38.985
2% percentile	27.751	27.373	31.184	31.648	36.546	36.087	36.563	35.216
1% percentile	27.363	26.840	30.496	31.110	35.962	35.318	36.117	34.368
0.1% percentile	26.349	25.347	28.530	29.600	34.429	33.162	34.995	31.992
0.01% percentile	25.584	24.118	26.880	28.358	33.265	31.388	34.189	30.038

5. OFFSET STRATEGY AND SIMULATION

With the knowledge on the distribution of the data, we are able to select the optimum offsets based on the distribution. This section will elaborate the simulation process in detail and present the results of the simulation.

5.1 Offset Strategy

Before setting up the simulation, desired offsets to be simulated is calculated first. The offsets are derived from the travel speeds which are selected from the various statistics of the distributions in the previous section. The distribution statistics to be used in offset calculation initially are:

The speed limit;
The average speed;
The data's 85th percentile speed;
The distribution's 85th percentile speed.

The reason to select these statistics is because compared to others, the mean and 85th percentile were able to represent the majority of the data. The speed limit was also selected because it is in theory coincide with the 85th percentile of speed data (20, 25). Considering the maximum speed in the simulation will be able to take care of the vehicles at the front of the platoon. It should also be noted that the maximum speed mentioned here refers to the fastest vehicle in the platoon. As mentioned previously, for cases where the link distance is long, there are very fast vehicles travelling greater than the speed limit. They will not be studied in the section and will be discussed in section 7. Discussion.

The offset values to be simulated correspond to the four speeds. Their values are listed in the following table, Table 6, under different link lengths.

Table 6. List of Offset Values to Be Simulated.

620 feet	speed limit	average speed	85th percentile	distribution's 85th percentile
Speed(mph)	45	31	34	33
Offset(sec)	9	14	12	13
1200 feet	speed limit	average speed	85th percentile	distribution's 85th percentile
Speed(mph)	45	36	37	38
Offset(sec)	18	23	22	22
1870 feet	speed limit	average speed	85th percentile	distribution's 85th percentile
Speed(mph)	45	42	44	45
Offset(sec)	28	30	29	28
2370 feet	speed limit	average speed	85th percentile	distribution's 85th percentile
Speed(mph)	45	42	45	45
Offset(sec)	45	42	45	45

During the simulation process, it is found that these offset values may not yield the optimum result, under certain degree of saturation or certain link lengths. Hence more offset values are calculated and input into the simulation. As a result, a range of values of offset were tested after the initial testing of the four proposed offset. The optimum offset value were selected based on the combined result.

5.2 Simulation Setup

Simulation was ran in Traffic Software Integrated System – Corridor System (CORSIM). CORSIM is a microscopic traffic simulation software package, including NETSIM and FRESIM. Here NETSIM is used since it is designed to simulate surface streets with intersection. The goal of simulation is to decide the optimum offset, under different conditions. The evaluation of offset strategy is based on the delay value resulted from CORSIM simulation. Besides link length, offsets will also be highly influenced by the degree of saturation. Hence the offset were tested under two different conditions: different link lengths and different degrees of saturation. Another situation that should be considered is when there are high cross street turning volume. At low degree of saturation, this should not be a big concern, as all vehicles are able to be progressed through the intersection. At high degree of saturation, on the other hand, longer residual queue will be formed due to high cross street volume. Further investigation on the optimum offset value is desire for this situation. Therefore, a case with cross street volume is added. The simulation cases are listed in Table 7.

Table 7. Cases to Be Simulated

Length	DOS				
620 feet	50%	70%	80%	90%	90%+cross street volume 400vph
1200 feet	50%	70%	80%	90%	90%+cross street volume 400vph
1870 feet	50%	70%	80%	90%	90%+cross street volume 400vph
2370 feet	50%	70%	80%	90%	90%+cross street volume 400vph

To start, two nodes were created first to symbolize two adjacent intersections located on the main street. They were connected by two-way links which represent the major/arterial street. Then minor/cross streets were added to connect to the two intersections. They could be used to investigate situations where cross streets have high turning volumes. In this way a layout of the surface street can be created, as shown in Figure 15.

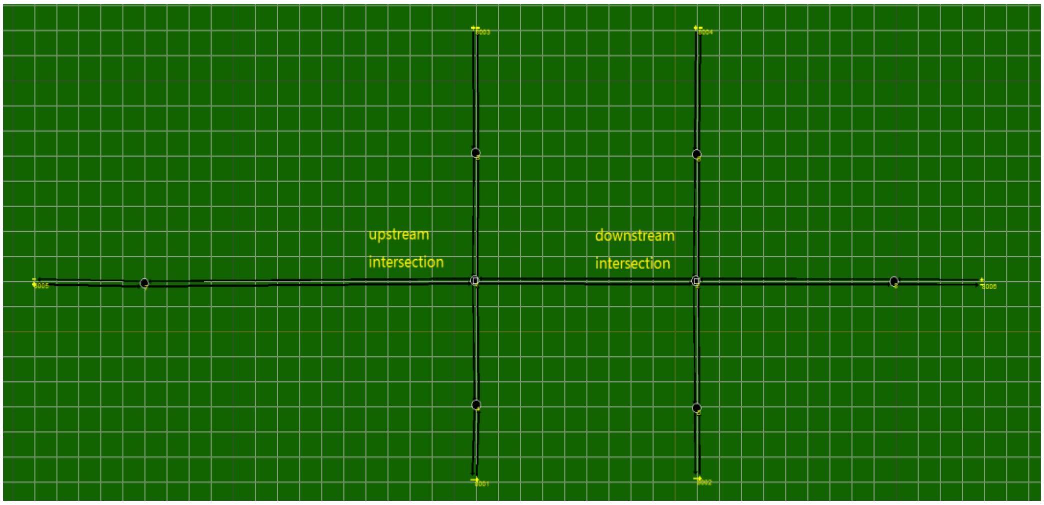

Figure 15. Surface Street Layout

The next step was to set the parameters and details of the intersections, links and vehicles. Both intersections had a cycle length of 150 seconds. This was to make sure that spillback would not occur on the upstream links, especially on the link between the intersections. Each intersection had a regular four phase timing strategy with protected lagging left turns. The through green was set to 90 seconds while yellow time and all red time were set to be 3 seconds and 2 seconds respectively. The links had two full lanes with 12 fit width, and left turn and right turn pockets of 350 feet at the intersection. The link lengths is adjusted for every case, from the Edit Link function. The vehicle volume was adjusted according to the degree of saturation at the entry nodes. Vehicle properties could be set at the Properties function of CORSIM. Since the report produce CORSIM only shows the delay by link, all vehicles are set to go through the downstream intersection. In this way the total link delay equals to the total through delay.

After translating the file, CORSIM could be run with a "multiple run" function. It automatically run the simulation for ten times, producing ten reports. The indices could be found from these reports. The simulation animation could be viewed through TRAFVU, as shown below. The cars were represented as blocks and signal indicators was added to better understand the vehicle behavior. The analysis on the result could be aided with observation on the animation, as shown in Figure 16.

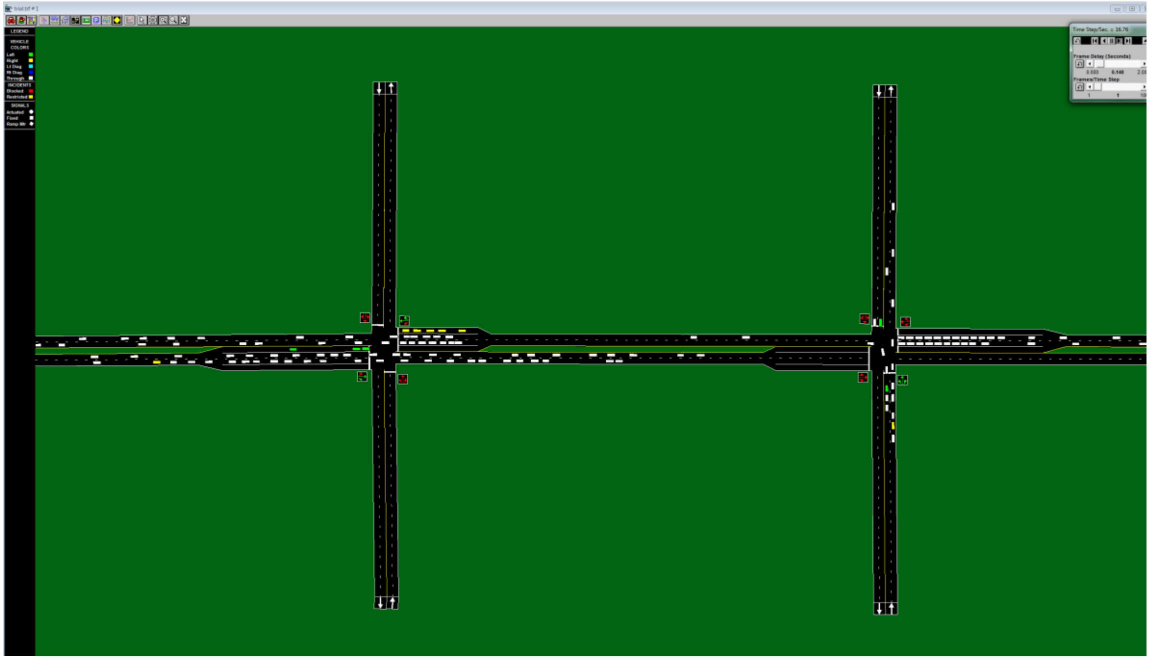

Figure 16. Screenshot of Simulation Run

5.3 Simulation Results

As mentioned, the simulation was run with a function called "multiple run" in CORSIM which will automatically run the simulation ten times. For each time, a report will be generated for that run including different simulation results, such as number of vehicles generated, number of stops, fuel consumption rate, etc. These results are measure for each link. The index that is interested here is the through delay at the downstream intersection where different offset values were tested. The ten offset values were recorded and an average value of the ten was used to represent the final delay value of a certain condition. This process was done for four different link lengths, 620, 1200, 1870 and 2370, under four degree of saturation conditions and a condition with cross street turning volume. Then the offset values with the smallest delay value was picked out to be the optimum offset. They are listed in Table 8 to Table 11 next page.

Table 8. Optimum Offset for 620 Feet Link

Length	620 feet				
Dos	50%				
	speed limit	average	85th percentile	distribution 85th	
Speed	45	31	34	33	
Offset	9	14	12	13	
Delay	95.8	82.1	81.4	81.4	
dos	70%				
	speed limit	average	85th percentile	distribution 85th	
speed	45	31	34	33	
offset	9	14	12	13	
delay	164.2	128.3	129.2	127.3	
dos	80%				
	speed limit	average	85th percentile	distribution 85th	
speed	45	31	34	33	28
offset	9	14	12	13	15
delay	220.5	127.3	145.7	134.8	127.2
dos	90%				
	speed limit	average	85th percentile	distribution 85th	
speed	45	31	34	33	28
offset	9	14	12	13	15
delay	221.4	126.6	142.6	133.3	124.5
dos	0.9		Cross street	400vph	
	speed limit	average	85th percentile	distribution 85th	
speed	45	31	34	33	
offset	9	14	12	13	
delay	296.8	218.6	231.3	220.2	

Table 9. Optimum Offset for 1200 Feet Link

length	1200 feet				
dos	50%				
	speed limit	average	85th percentile	distribution 85th	
speed	45	36	37	38	34
offset	18	23	22	22	24
average	160.5	134.7	136.1	136.1	133.7
dos	70%				
	speed limit	average	85th percentile	distribution 85th	
speed	45	36	37	38	34
offset	18	23	22	22	24
	281.3	218	223.7	223.7	213.6
dos	80%				
	speed limit	average	85th percentile	distribution 85th	
speed	45	36	37	38	31
offset	18	23	22	22	26
average	350	229.7	247.8	247.8	203.6
dos	90%				
	speed limit	average	85th percentile	distribution 85th	
speed	45	36	37	38	31
offset	18	23	22	22	26
average	337.8	222.6	242	242	201.6
dos	90%		cross street	400vph	
	speed limit	average	85th percentile	distribution 85th	
speed	45	36	37	38	34
offset	18	23	22	22	24
average	337.8	317.8	330.7	330.7	304.6

Table 10. Optimum Offset for 2870 Feet Link

length	1870 feet				
dos	50%				
	speed limit	average	85th percentile	distribution 85th	
speed	45	42	44	45	35
offset	28	30	29	28	36
average	244.4	227.1	234.6	244.4	203.5
dos	70%				
	speed limit	average	85th percentile	distribution 85th	
speed	45	42	44	45	34
offset	28	30	29	28	38
	445.8	408.6	427.3	445.8	324.7
dos	80%				
	speed limit	average	85th percentile	distribution 85th	
speed	45	42	44	45	33
offset	28	30	29	28	39
average	525.8	479.8	507.2	525.8	314.4
dos	90%				
	speed limit	average	85th percentile	distribution 85th	
speed	45	42	44	45	33
offset	28	30	29	28	39
average	507.3	467.5	481	507.3	309.5
dos	90%		cross street	400vph	
	speed limit	average	85th percentile	distribution 85th	
speed	45	42	44	45	35
offset	28	30	29	28	37
average	620.2	553.1	586.1	620.2	423.9

Table 11. Optimum Offset for 2370 Feet Link

length	2370 feet				
dos	50%				
	speed limit	average	85th percentile	distribution 85th	
speed	45	42	45	45	36
offset	36	38	36	36	45
average	305.8	288.7	305.8	305.8	259.4
dos	70%				
	speed limit	average	85th percentile	distribution 85th	
speed	45	42	45	45	35
offset	36	38	36	36	47
	563	526.3	563	563	411.7
dos	80%				
	speed limit	average	85th percentile	distribution 85th	
speed	45	42	45	45	33
offset	36	38	36	36	49
average	674.7	599.3	674.7	674.7	406
dos	90%				
	speed limit	average	85th percentile	distribution 85th	
speed	45	42	45	45	33
offset	36	38	36	36	49
average	641.8	586.6	641.8	641.8	400.2
dos	90%		cross street	400vph	
	speed limit	average	85th percentile	distribution 85th	
speed	45	42	45	45	34
offset	36	38	36	36	48
average	733.2	688.5	733.2	733.2	513.3

6. RESULT COMPARISONS AND CONCLUSIONS

As mentioned previously, a range of offset values were tested. The resulted delay values were made in into graphs to formulate the delay versus offset curves. A sample graph, Figure17, is shown below while the rest of the curves can be found in Appendix B Delay vs. Offset Graphs. From the graph, an optimum offset value can be found corresponding to a minimum delay value. Increasing or decreasing the offset will result in larger delay.

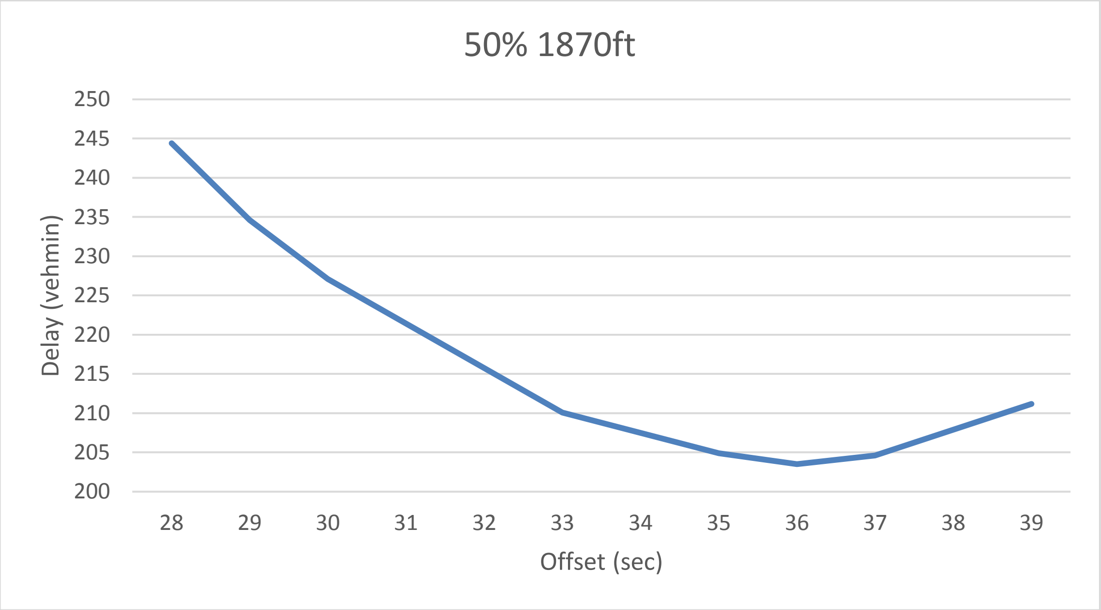

Figure 17. Sample Graph: Delay vs. Offset

To summarize, it can be found from the simulation results that for short link length (620 feet) at lower degree of saturation (50% and 70%), the optimum offset is about the distribution’s 75% percentile speed value. On the other hand, for short link (620 feet) at

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higher degree of saturation (80% and 90%), the optimum offset is about the value of the 4% percentile speed. For the 1200 feet link, the offset is about the value of the 20% percentile speed under low degree of saturations (50% and 70%). At high degree of saturation, the offset is about the value of the 2% percentile speed on the 1200 feet link. For longer links however, the offset should be increased to a larger value which corresponds to a speed that is slower than 99% of the vehicles (the 1% percentile speed) in order to yield the shortest delay at low degree of saturation. The percentile speeds which the offsets are based on are furthered decreased as the degree of saturation increases, yielding a large offset. This high offset value will stop the platoon at the downstream intersection but produce a shorter delay value than an early offset. This is due to the platoon dispersion at longer link lengths. At shorter link lengths, the platoons are still compact and an early offset will be able to proceed all the vehicles through the downstream intersection when the degree of saturation is low. Thus the offset strategy should be focused on the front of the platoon. It should be set early in order to let more vehicles at the front pass without stopping. When the degree of saturation increases, it becomes hard for the vehicles at the back of the platoon to pass through the intersection if an early offset is still implemented. An offset corresponding to the minimum speed is preferred here to take rear vehicles into account. As the link distance increases, the platoons will have larger dispersion with longer length and higher variation of speeds, making it even harder for the vehicles at the back of the platoon to pass through the intersection. From the simulation it can be observed that an early offset will stop more vehicles at the back while proceeding vehicles at the front of the platoon. The rear vehicles will produce larger delay as they are stopped and wait at the intersection. The delay caused by these queued vehicles is much larger than the time reduced from progressing front vehicles without stopping. The goal of the offset strategy now becomes reducing the number of vehicles that are not able to pass through the intersection. Hence it is not surprising to see very large offset values at the downstream intersection, since a larger value reduces number of queued vehicles.

One more situation to consider is that when the upstream cross streets have higher turning volume. In this case, the turning vehicles are stopped by the red signal on the arterial street. The simulation result shows that it is better to reduce the offset by about 2 seconds in order to have the shortest delay. These vehicles are causing more delay as they are stopped by the red light and the offset needs to be adjusted earlier in order to provide extra time for these queued vehicles to dissipate. The results are listed in Table 12.

Table 12. Optimal Offset under Different Scenarios

	620 ft	1200 ft	1870 ft	2370 ft
50%	13(75%)	24(20%)	36(1%)	45(1%)
70%	13(75%)	24(20%)	38(0.02%)	47(0.01%)
80%	15(4%)	26(2%)	39(0.005%)	49(0.0001%)
90%	15(4%)	26(2%)	39(0.005%)	49(0.0001%)
Residual queue	14(70%)	24(20%)	37(0.1%)	48(0.001%)

The following graphs, Figure 18 to 21 compare the optimum offset for different degree of saturation at the same link lengths. It can be found that at shorter links (620 and

1200), the offset are not influenced much by the degree of saturation at beginning. When the degree of saturation increases from 70% to 80%, there is a sudden increase in the offset. For longer links (1870 and 2370) on the other hand, the offset increases as the degree of saturation increases. This pattern may be explained by the fact that platoons have larger dispersion at longer links. Increasing the degree of saturation means more vehicles are produced and the tail of the platoon gets longer. Hence the offset are more “sensitive” to the change in degree of saturation at longer links. The offset remains unchanged if the degree of saturation is further increased from 80% to 90%. This may indicate the fact that increasing the offset at 90% degree of saturation may be not as efficient as low degree of saturation in terms of reducing delay, since more vehicles are stopped in front. Reducing delay caused by vehicles at the back will not be able to compensate for the delay caused by the vehicles at front.

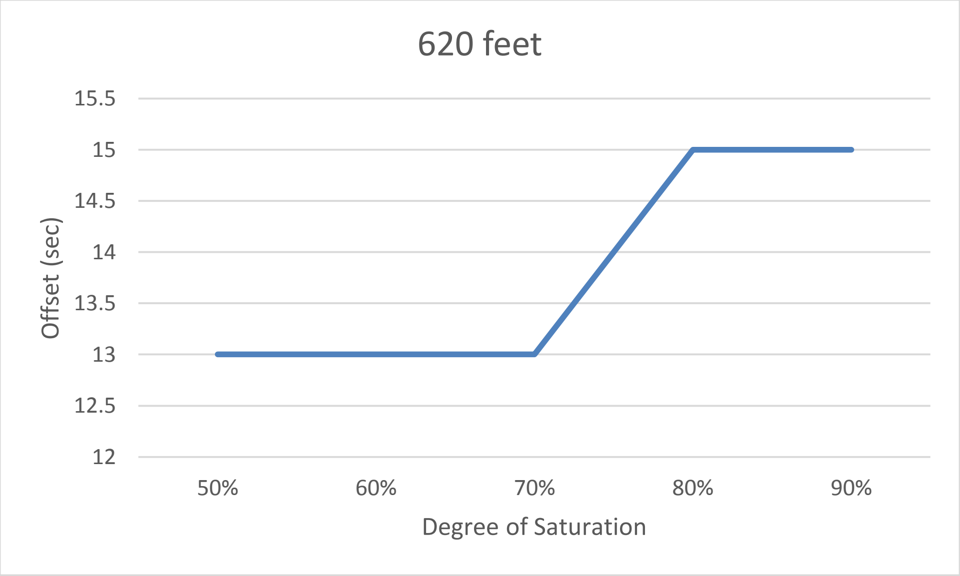

Figure 18. Offset vs. DOS, 620 Feet

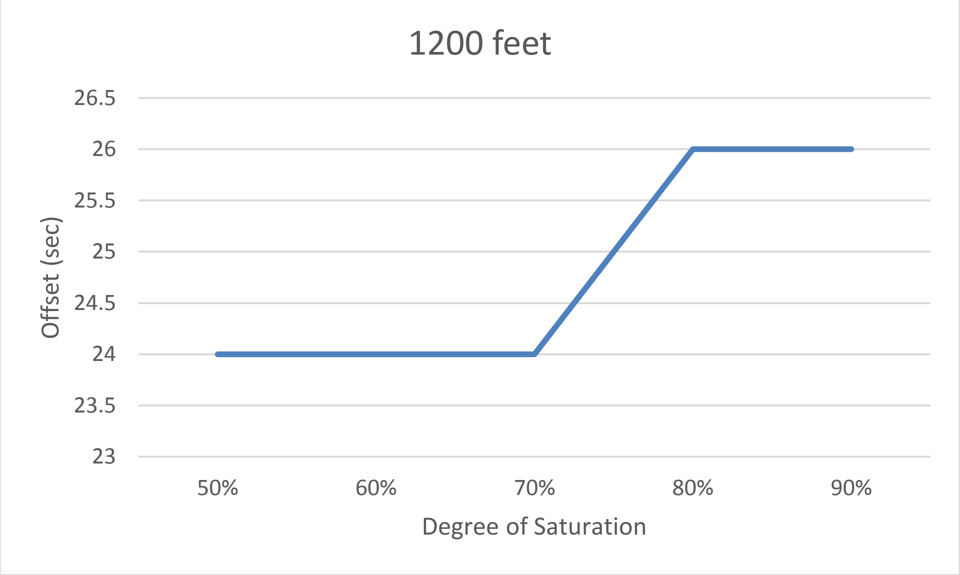

Figure 19. Offset vs. DOS, 1200 Feet

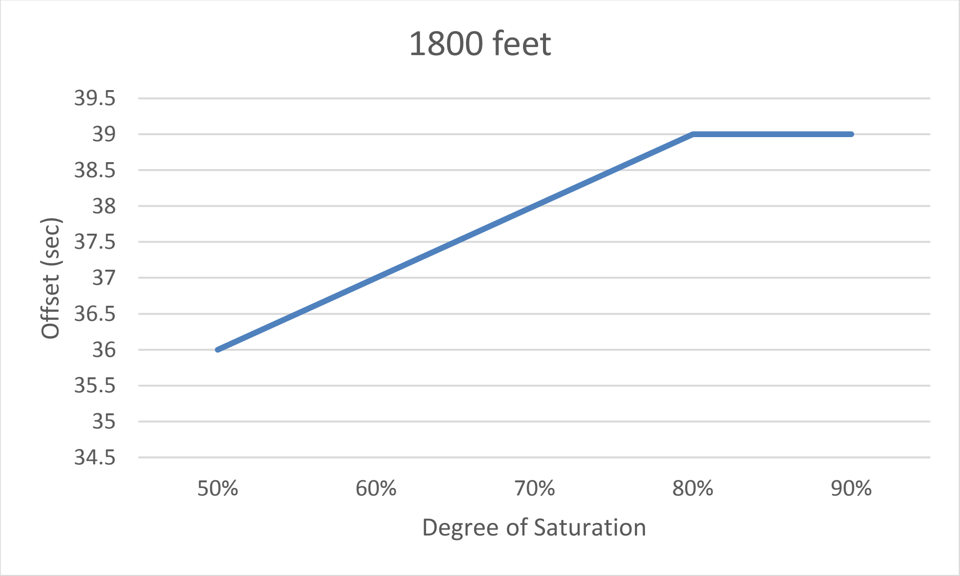

Figure 20. Offset vs. DOS, 1870 Feet

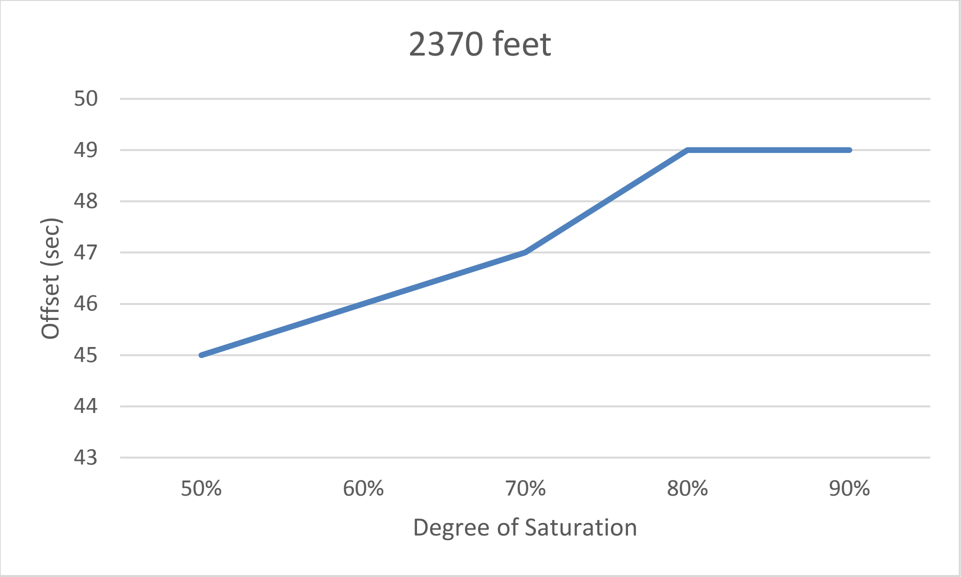

Figure 21. Offset vs. DOS, 2370 Feet

7. DISCUSSION AND RECOMMENDATIONS

The study demonstrated that the generalized extreme value distribution has greater advantage than the normal distribution to describe variables in platoon traffic, especially at higher degree of saturation and longer links. The simulation results also demonstrated the application value of this distribution when selecting the best offset strategy, as offsets based on low percentile speed values from this theoretical distribution are often used in various traffic and link length conditions. In those scenarios of higher degrees of saturation with long links, the offset values are adjusted to be very large in order to accommodate the slow vehicles. This shows the importance of the rear vehicles and they need to be modelled well. The type III generalized extreme value distribution has the ability to model the lower tail well and therefore outperforms the normal distribution.

It should be noted, on the other hand, that some potential source of errors exists during the data collection and handling process. In order to collect the travel time data of the longer links, estimation method was used at the data collection point. Since the link distance is as long as 2370 feet, the starting point was not identified clearly. Hence some systematic error may occur. In addition, since the speed data is obtained by dividing distance by time, some bias may also occur during this process.

As mentioned previously, a few vehicles were travelling at a much faster speeds and arrived much earlier than the real platoon. One consideration was whether the offset needed to be adjusted earlier for these vehicles. In fact, these vehicles travels even faster than the speed limit. Considering that one function of signal coordination is to control the speed and stop vehicles that are travelling too fast, it is debatable if the offset should be set earlier for speeding vehicles, just for the purpose of reducing delay.

The strategy of a late offset also have another advantage of re-compacting the platoons, as vehicles are stopped by the signals. The signal coordination will be not functioning at all at some point due to platoon dispersion. Hence it is necessary to re-compact the platoon at a desired distance. The vehicles with high variation of speeds and headways will be regrouped to platoons with closer speeds and headways. With a much more compact re-compact platoon, signal coordination at downstream intersection will be more effective.

The result shows the dominance of delay produced by vehicles stopped at the end of the green phase over the delay produced by vehicles stopped before the beginning of green phase. Since the optimality of offsets was measured in terms of delay, the goal of optimization will be reducing the proportion of vehicles that were unable to pass the intersection during the green phase as much as possible. The focus on delay result in a late offset at the downstream intersection. This strategy however, may produce a larger total number of stops, as more vehicles are stopped by the red signal. The effect of these stops on different considerations like emission, fuel consumption is unclear. Hence further investigation could be made with a comprehensive consideration on the total delay, total number of stops, emission, fuel consumption, etc.

In order to obtain an accurate through delay, all vehicles were set to have the through movement at the downstream intersection. In real-life situation, however, the through vehicles may be influenced by other vehicles that change lanes in order to make left or right turns. These vehicles will affect both the headway and travel speeds of the vehicles in the platoon, especially when their proportion is high. How the distributions of the variables are influenced and the offsets should be changed based on the vehicles that change lanes require further investigation. Another improvement that could be made is the study on the influence of trucks. The platoon characteristics may change with different truck percentage as slower travelling speeds or larger headways may be expected. How the distribution pattern changes with these factors requires further studies.

More future studies could also be done on the study of start-up process. For the shortest link (620 feet), the distribution does not show a good pattern. This is because short links are highly influenced by the start-up process which differs from normal driving scenario. The study on distribution of start-up process and its transition to normal driving is desired in order to understand platoon characteristics for shorter links. Furthermore, this study was conducted based on the as setup of only two intersections. In real world, however, there often exists a series of intersections and coordination should be done for all of them. An extended study on multiple intersections will be able to yield a result that is more applicable.

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APPENDIX A

GOODNESS-OF-FIT TESTS

Table A-1 Goodness-of-fit Test Results for Travel Time Data

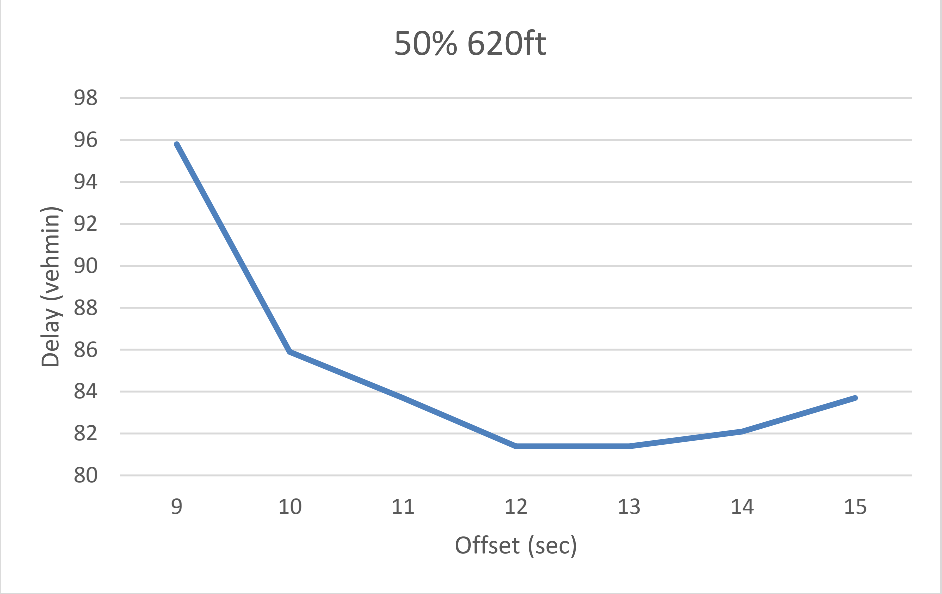
	620 feet	1200 feet	1870 feet	2370 feet
Normal				
SW	0.960449	0.938575	0.992537	0.982601
KS	0.07704	0.1262	0.04301	0.06487
AD	1.7348	3.8729	0.36403	1.154
Weibull				
KS	0.09796	0.176	0.07612	0.05961
AD	3.2817	10.881	2.213	0.70213
Lognormal				
KS	0.07695	0.11566	0.04539	0.06694
AD	1.9205	3.0152	0.42318	1.679
3P Gamma				
KS	0.07395	0.08582	0.04462	0.06126
AD	1.9539	1.7149	0.40725	1.3679
Extreme Value				
KS	0.06939	0.05852	0.03541	0.04187
AD	1.5381	1.1636	0.22935	8.2069

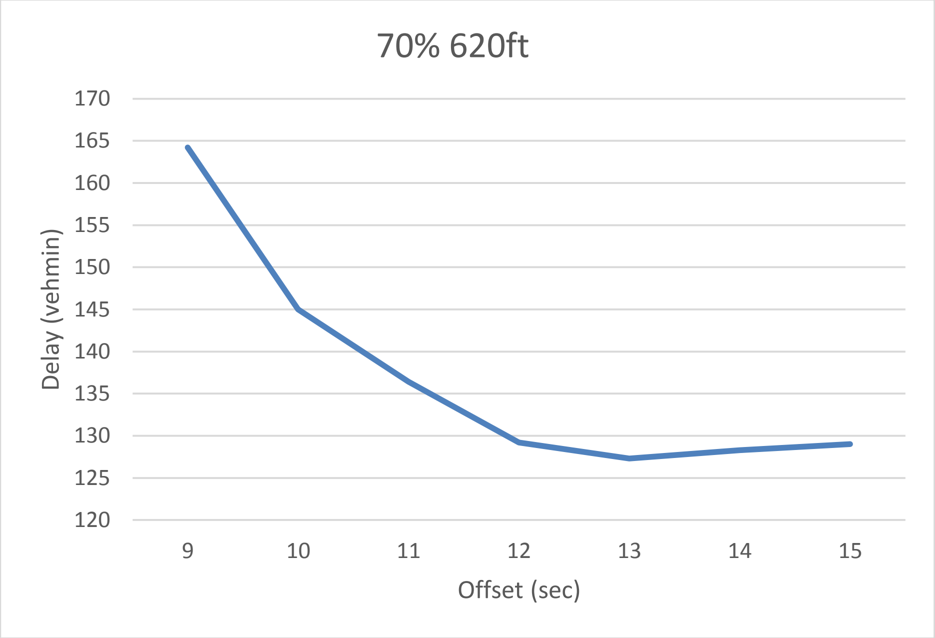
Table A-2 Goodness-of-fit Test Results for Speed Data

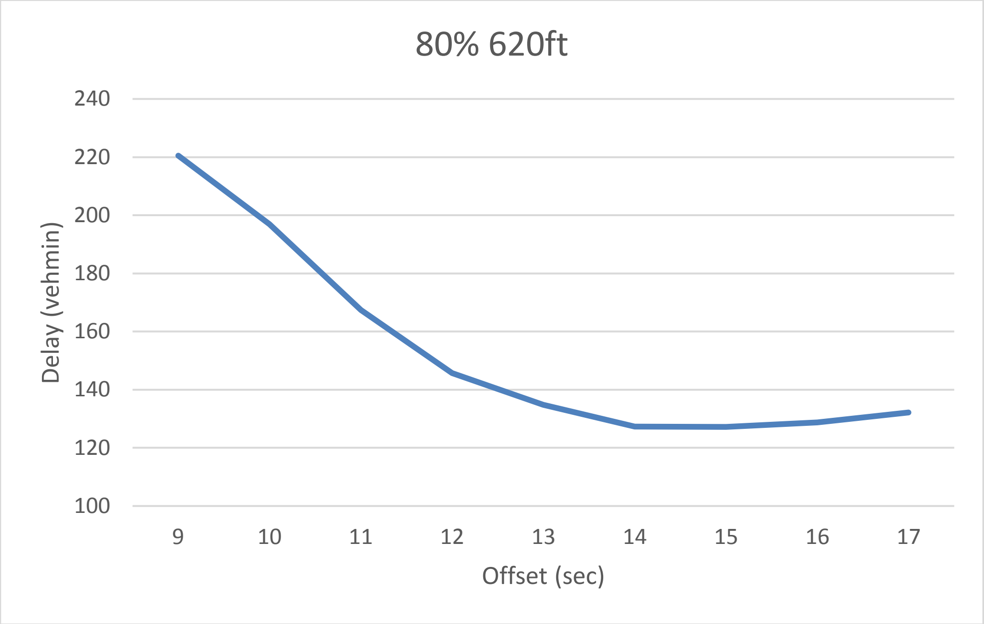
	620 feet	1200 feet	1870 feet	2370 feet
Normal				
SW	0.955464	0.965423	0.98908	0.961934
KS	0.07501	0.10476	0.05796	0.07732
AD	2.2037	2.3329	0.59886	2.3518
Weibull				
KS	0.1153	0.05349	0.10541	0.12486
AD	6.1971	1.2783	3.5779	7.2808
Lognormal				
KS	0.07695	0.11566	0.04539	0.06694
AD	1.9205	3.0152	0.42318	1.679
3P Gamma				
KS	0.07744	0.12447	0.04157	0.05382
AD	1.7744	3.2153	0.34488	0.57411
Extreme Value				
KS	0.06987	0.06662	0.03463	0.05233
AD	1.5485	24.602	0.24045	0.4912

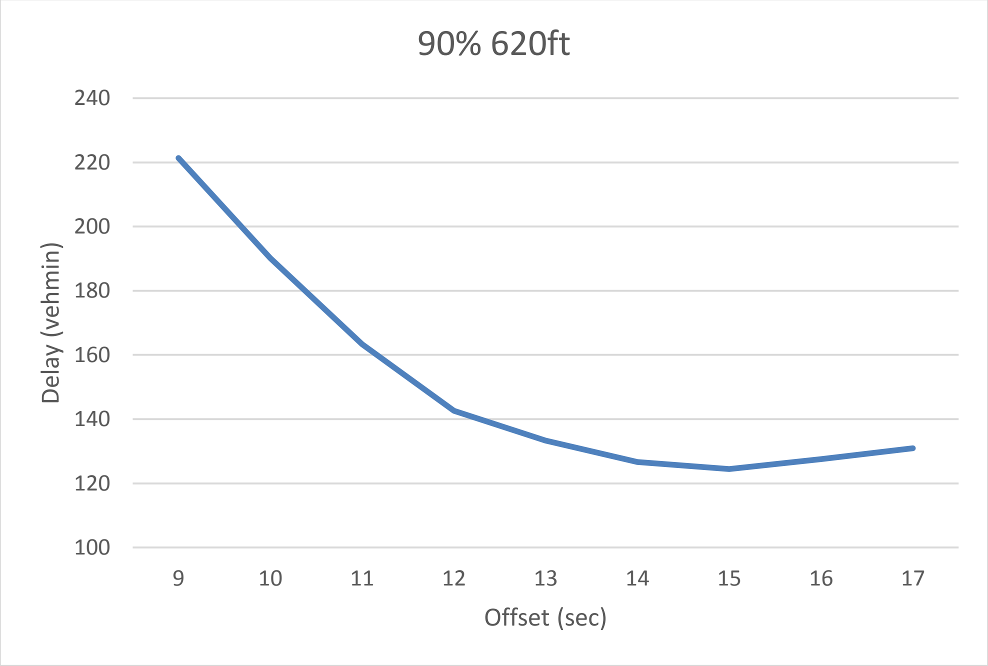
APPENDIX B

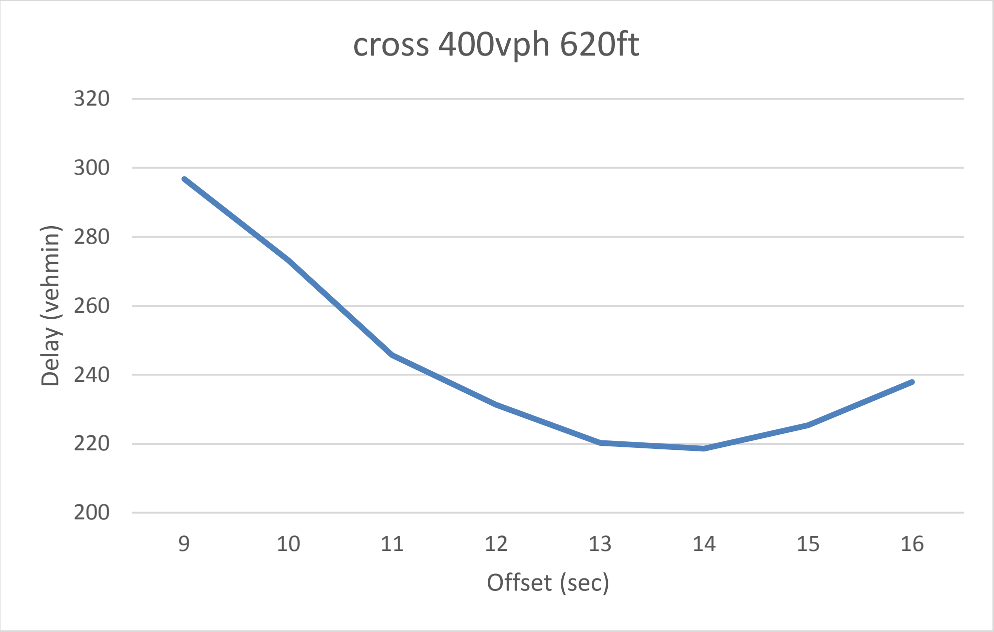
DELAY VS. OFFSET GRAPHS

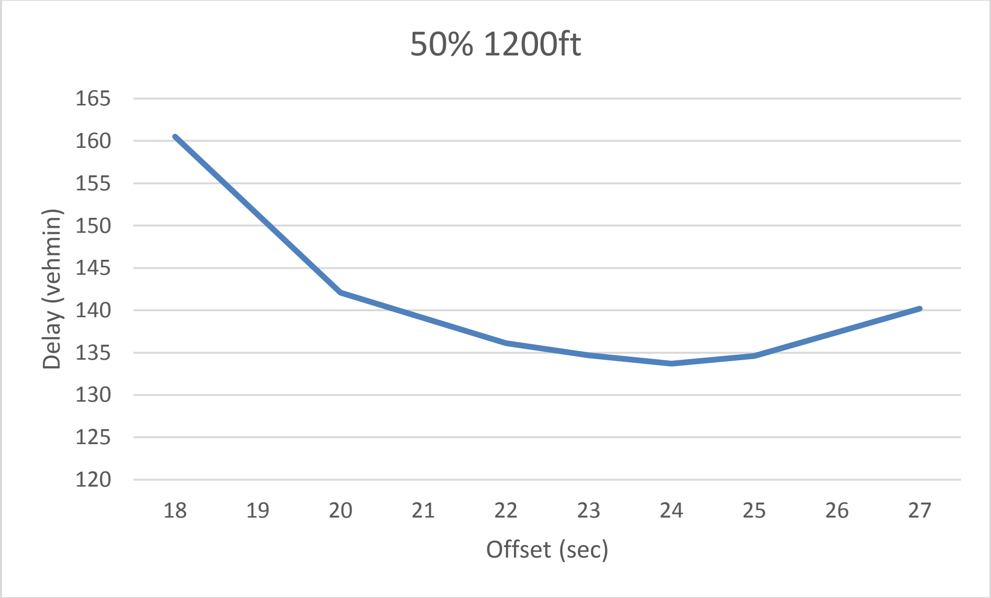


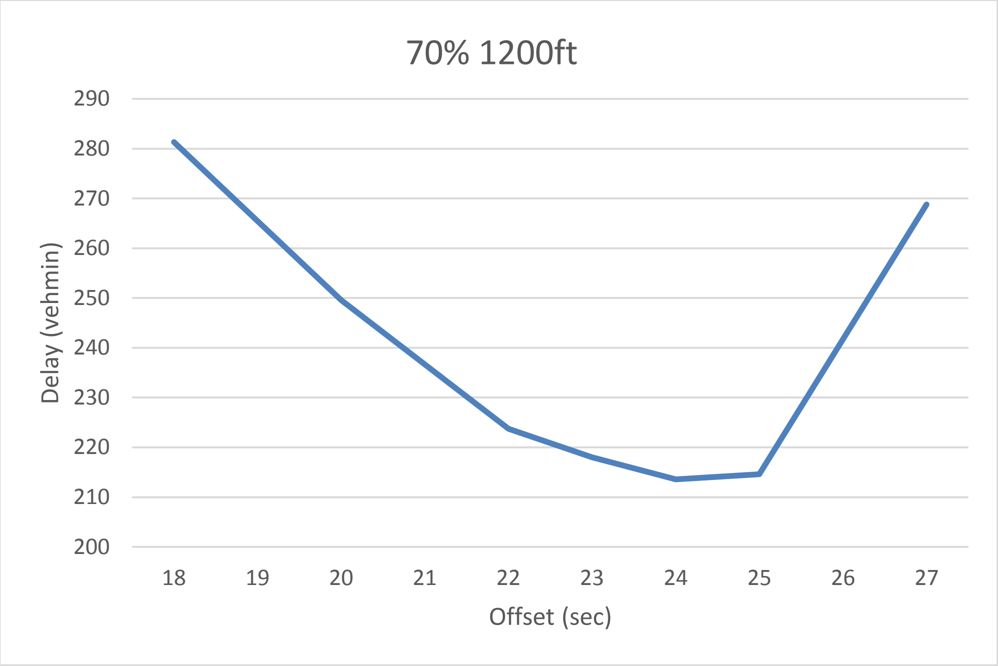


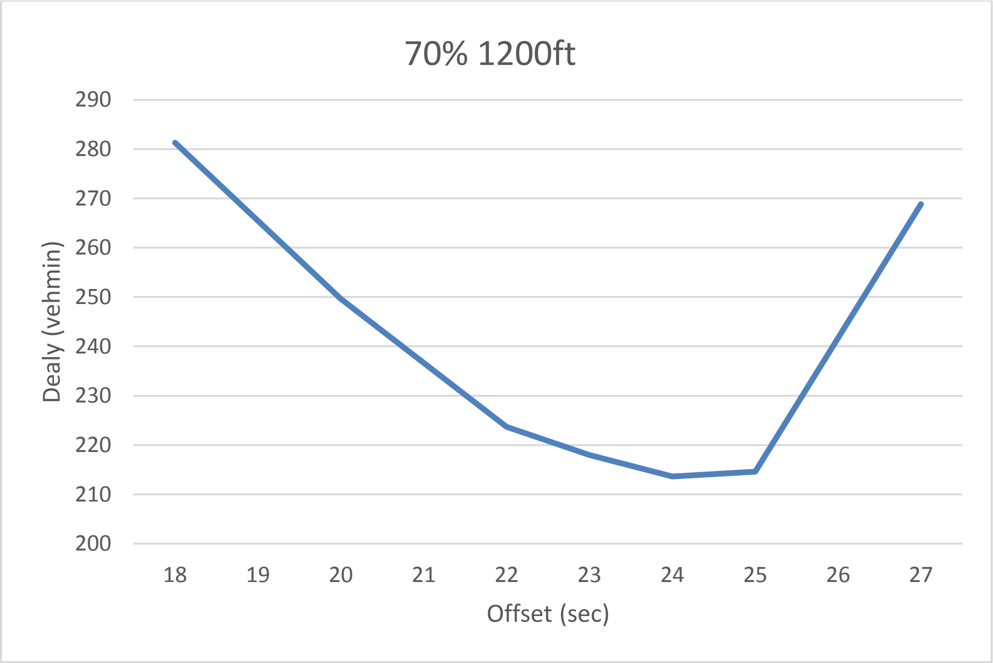

80% 620ft
Delay (vehmin)
240
220
200
180
160
140
120
100
9
10
11
12
13
14
15
16
17
Offset (sec)

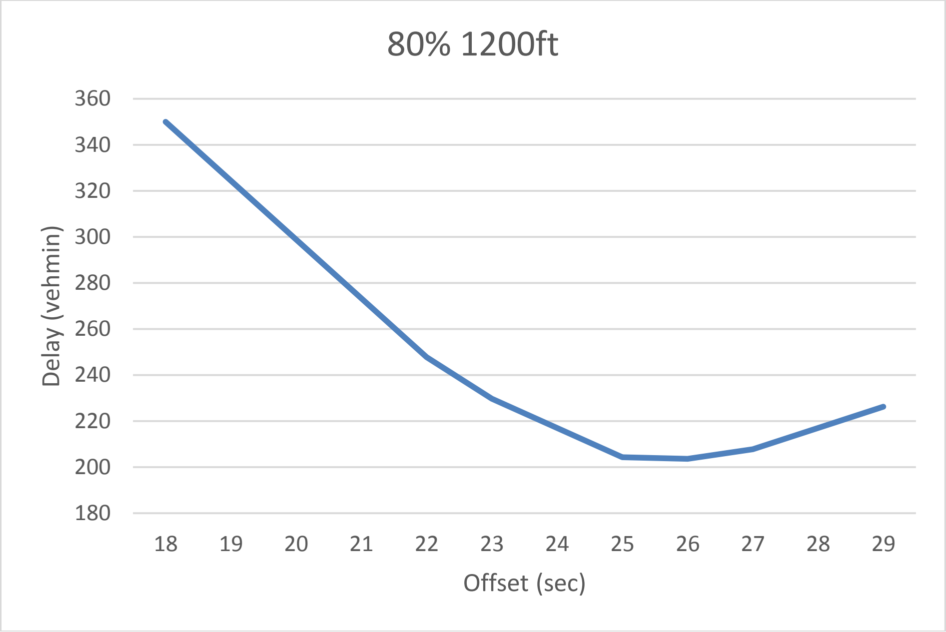

90% 620ft
Delay (vehmin)
240
220
200
180
160
140
120
100
9
10
11
12
13
14
15
16
17
Offset (sec)

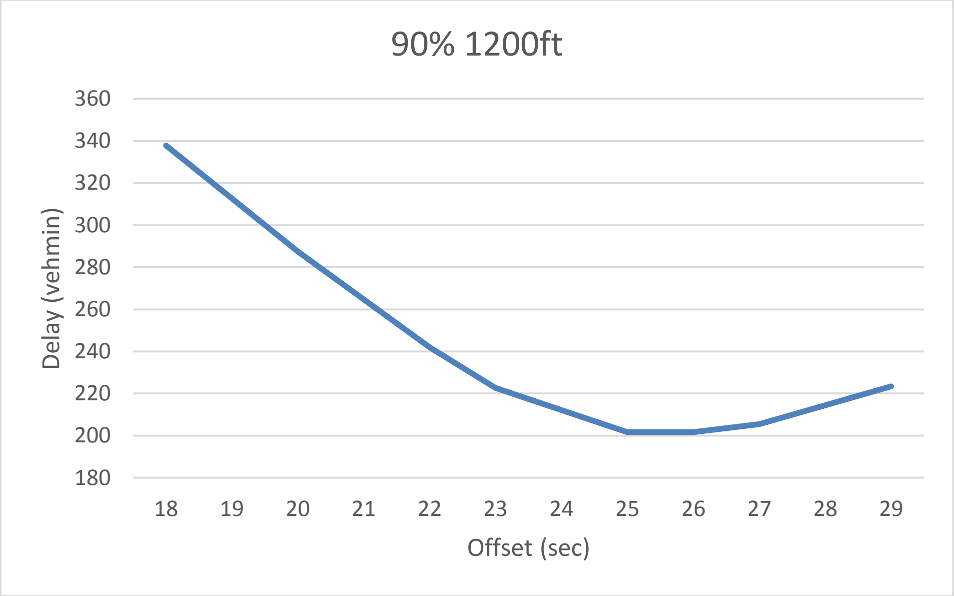

cross 400vph 620ft
Delay (vehmin)
320
300
280
260
240
220
200
9
10
11
12
13
14
15
16
Offset (sec)

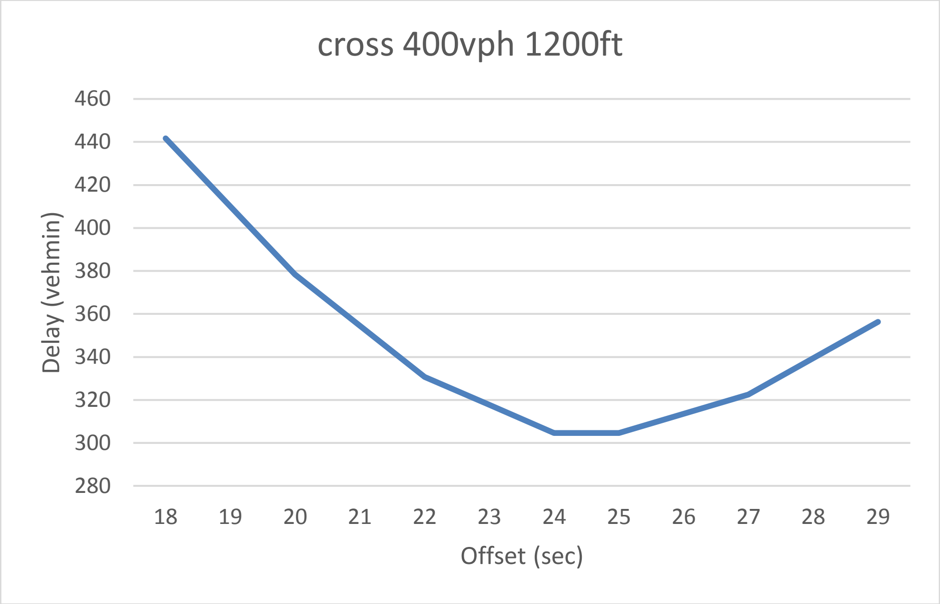

50% 1200ft
Delay (vehmin)
165
160
155
150
145
140
135
130
125
120
18
19
20
21
22
23
24
25
26
27
Offset (sec)

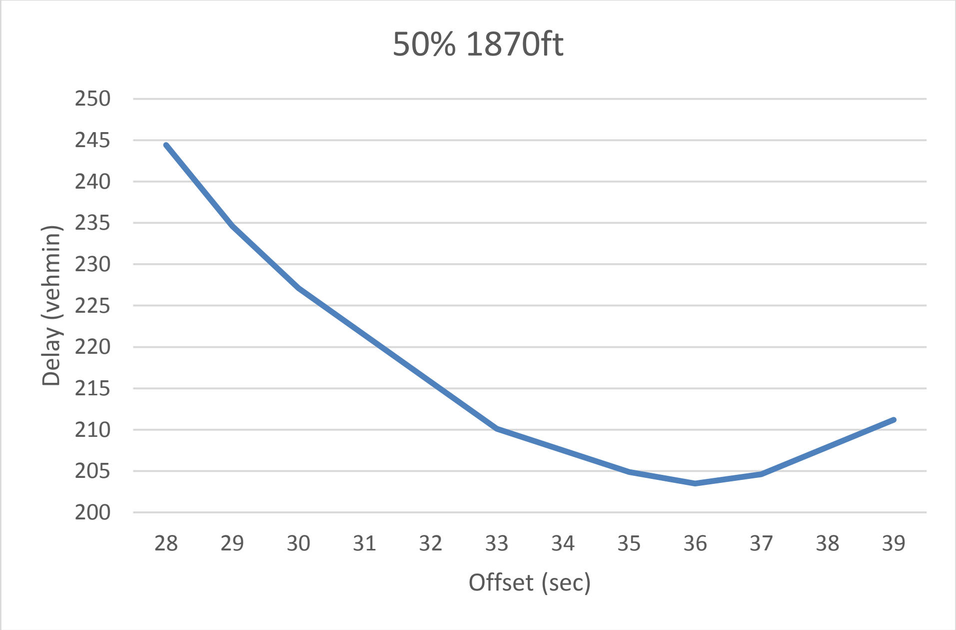

70% 1200ft
Delay (vehmin)
290
280
270
260
250
240
230
220
210
200
18
19
20
21
22
23
24
25
26
27
Offset (sec)

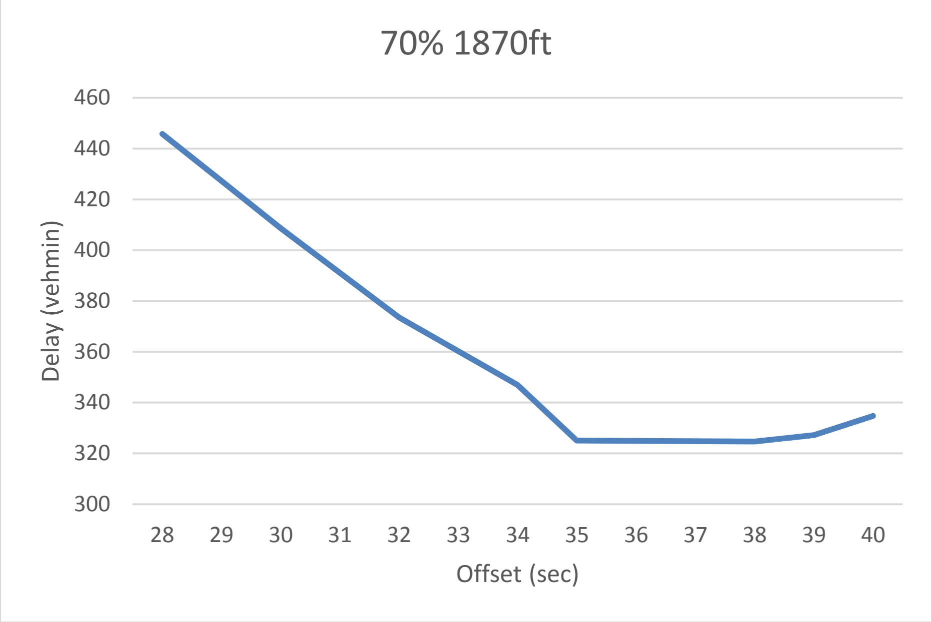

70% 1200ft
Dealy (vehmin)
290
280
270
260
250
240
230
220
210
200
18
19
20
21
22
23
24
25
26
27
Offset (sec)

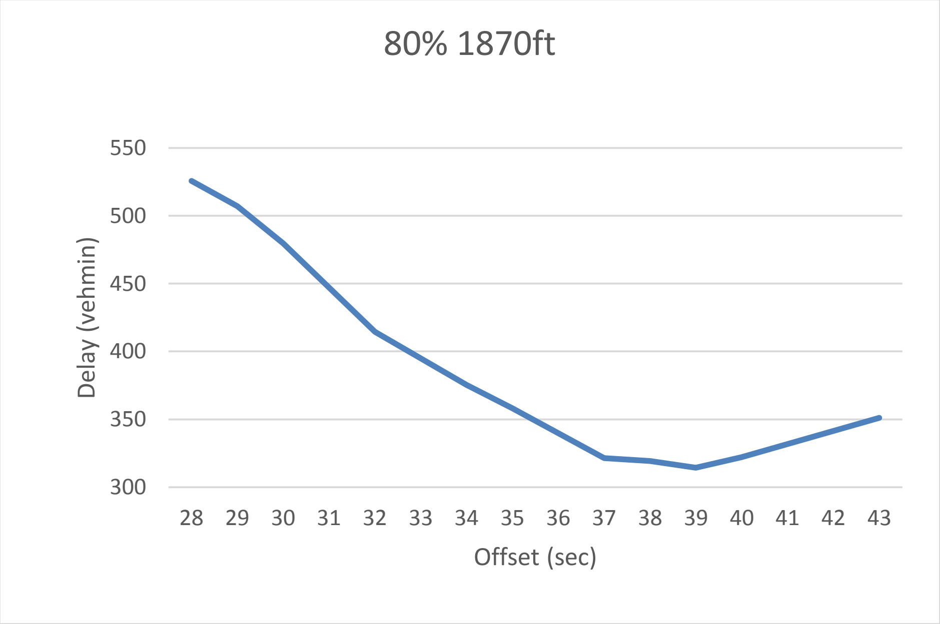

80% 1200ft
Delay (vehmin)
360
340
320
300
280
260
240
220
200
180
18
19
20
21
22
23
24
25
26
27
28
29
Offset (sec)

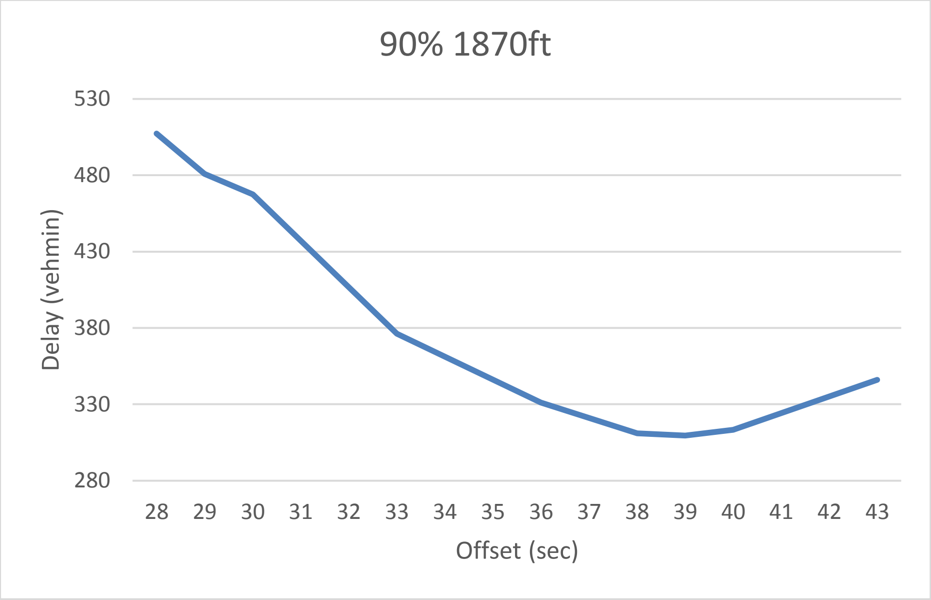

90% 1200ft
Delay (vehmin)
360
340
320
300
280
260
240
220
200
180
18
19
20
21
22
23
24
25
26
27
28
29
Offset (sec)

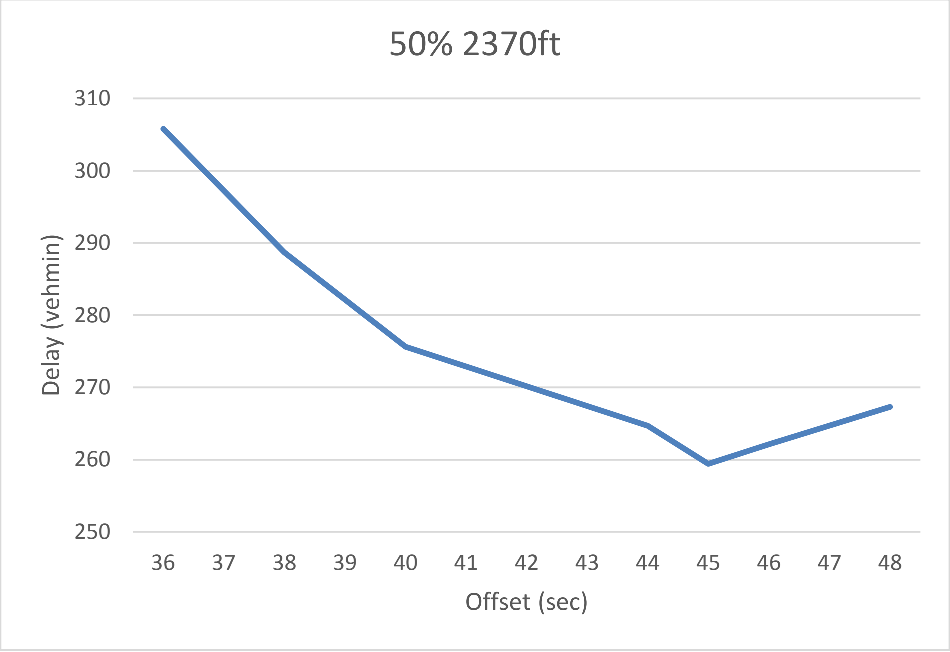

cross 400vph 1200ft
Delay (vehmin)
460
440
420
400
380
360
340
320
300
280
18
19
20
21
22
23
24
25
26
27
28
29
Offset (sec)

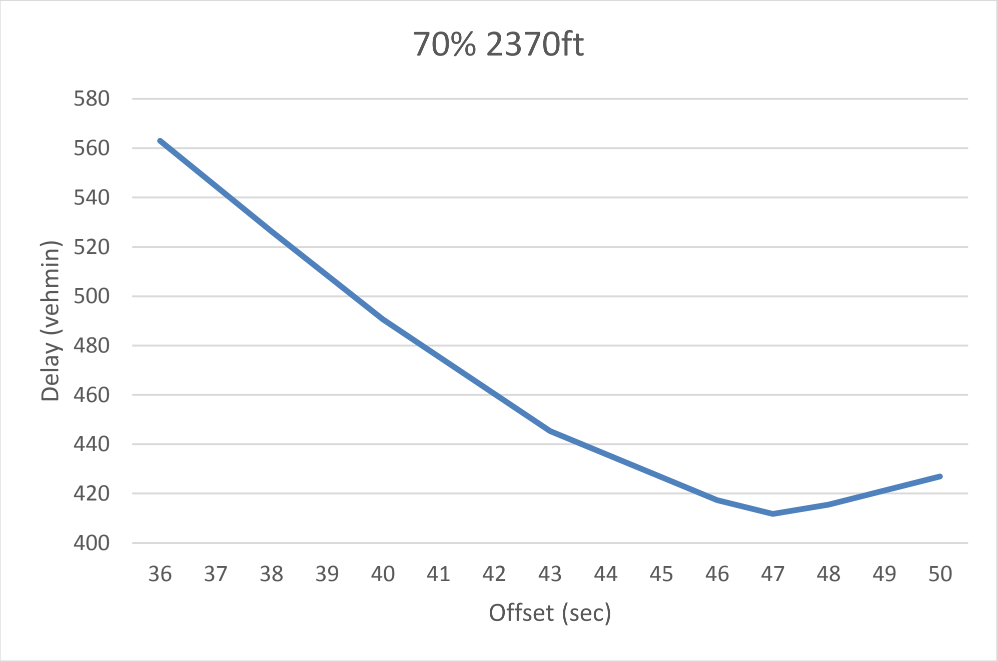

50% 1870ft
Delay (vehmin)
250
245
240
235
230
225
220
215
210
205
200
28
29
30
31
32
33
34
35
36
37
38
39
Offset (sec)

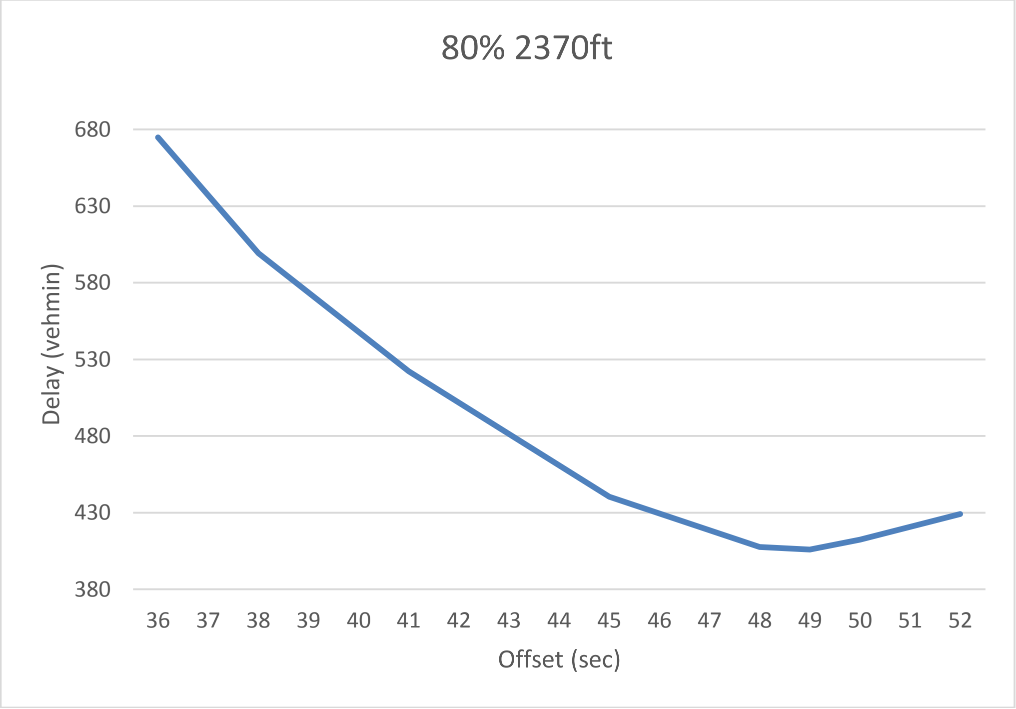

70% 1870ft
460
440
420
400
380
360
340
320
300
Delay (vehmin)
28
29
30
31
32
33
34
35
36
37
38
39
40
Offset (sec)

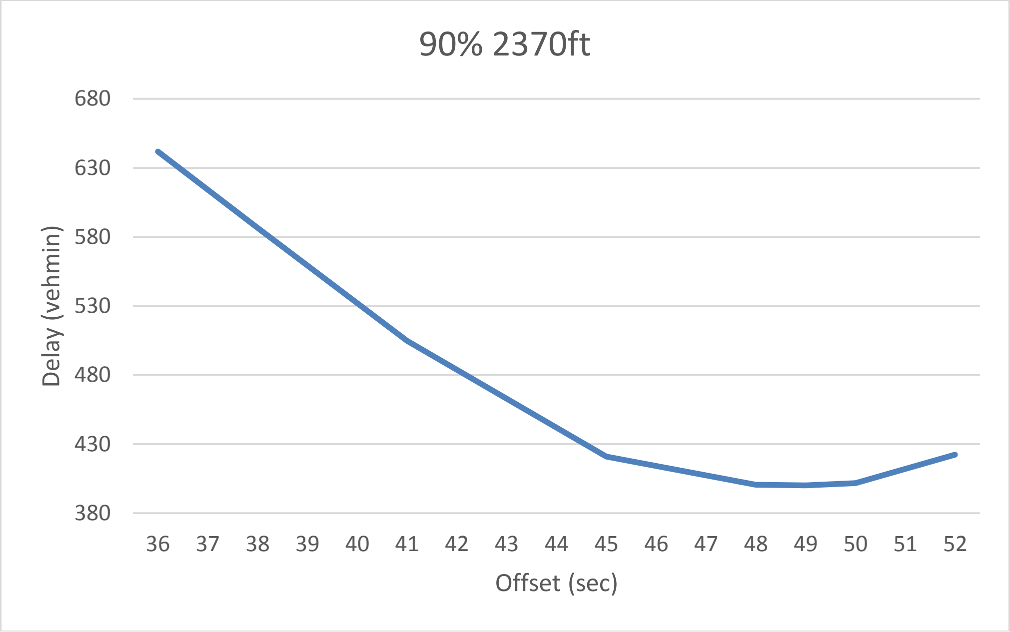

80% 1870ft
550
500
450
400
350
300
Delay (vehmin)
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
Offset (sec)


90% 1870ft
Delay (vehmin)
530
480
430
380
330
280
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
Offset (sec)


50% 2370ft
Delay (vehmin)
310
300
290
280
270
260
250
36
37
38
39
40
41
42
43
44
45
46
47
48
Offset (sec)


70% 2370ft
Delay (vehmin)
580
560
540
520
500
480
460
440
420
400
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
Offset (sec)


80% 2370ft
Delay (vehmin)
680
630
580
530
480
430
380
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
Offset (sec)


90% 2370ft
680
630
580
530
480
430
380
Delay (vehmin)
36
37
38
39
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42
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44
45
46
47
48
49
50
51
52
Offset (sec)


cross 400vph 2370ft
800
750
700
650
600
550
500
Delay (vehmin)
36
37
38
39
40
41
42
43
44
45
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47
48
49
50
51
52
Offset (sec)