CAR FOLLOWING UNDER REDUCED VISIBILITY

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ABSTRACT

Driving in fog is a challenging task. ITS application through Changeable Message Sign (CMS) is one of the popular ways to assist drivers in fog. However, an evaluation done on California's Automated Warning System (CAWS) showed that "a generic advisory speed" for a traffic stream is not effective in modifying driver's behavior for better safety. On the other hand existing literature shows that "in-vehicle headway feedback" may be effective in modifying driver behavior. However, to provide such feedback, it is essential to build understanding about safe headways in various visibility conditions. Estimate of such safe headways may be obtained by analyzing drivers' car-following behavior in reduced visibility. In this study real life data on fog driving, containing records such as time of arrival and departure, speed, headway and vehicle lengths are used to study driver's headway maintenance with speed. Investigation is done to check headway variation with respect to speed at the study location. The results indicate no variation across sites but clear variation of headway with respect to speed across lanes. It is also observed that for a particular speed under similar visibility condition, headway value is the least in the fast lane. Graphs with cumulative distribution of headways are plotted to find 85th percentile headways across various sites and lanes for a particular visibility level. To measure the propensity and severity of collision Time to Collision (TTC) and Potential Collision Speed (PCS) are computed and used as surrogate safety measures. Also, recommendations for safe headways are made for specific visibility condition.

Keywords: Car-following, reduced visibility, fog, safe headway, TTC, PCS

INTRODUCTION AND BACKGROUND

Driving in fog is a challenging task. In California's central valley poor visibility due to fog is a significant concern, which leads to rear end and multi-vehicle crashes during the months from October to April. To guide drivers in dense fog, California Department of Transportation (Caltrans) has installed an Automated Warning System known as Caltrans Automated Warning System (CAWS), a fully-automated fog and traffic warning system in the central valley along a 15 mile stretch of Interstate 5 and State Route 120. CAWS generates automated driver warning and advisory messages on changeable (variable) message sign (CMS) board to guide drivers during seasonal Tule fog. CAWS system first became operational in November 1996. A team under the lead of Prof. Art MacCarley at Cal Poly San Luis Obispo, under contract to the California Office of Traffic Safety, was responsible for evaluating the effectiveness of the Caltrans Automated Warning System (CAWS), which required the development and deployment of advanced instrumentation to record microscopic traffic flow parameters such as individual vehicle speed, time of detection, separation, vehicle length etc. While evaluating the effectiveness of the CAWS, MacCarley et al. (2007) identified that even though the advisory messages evoked a measurable effect on driver behavior, it was well below design expectations. In addition they noted that drivers appeared to respond predominantly to their own perceptions. There was also some evidence that the CMS actually resulted in more densely packed platoons as most of the drivers, who ignored the CMS message, accumulated behind the conforming drivers and reduced their separation distance to less safe levels for the given speed and visibility. On the other hand evidences (Shiner and Schechtman, 2002) show that "in-vehicle headway feedback" is very effective in modifying driver behavior. Based on these observations it is concluded that individual rather than general overall message would be more effective in ensuring safety in reduced visibility due to fog.

It is well observed (Evans and Rithery, 1976; Evans, 2004; Broughton et. al, 2007) that in fog drivers tend to follow the leading vehicles too closely from the fear of losing a reference. This leads to a situation of car following where the following drivers' choice of appropriate headway is very important for safety. By studying car following phenomena it is possible to understand drivers' behavior and how they react to certain road conditions such as reduced visibility due to fog—the focus of the present study. The headway that a driver must maintain to avoid potential collision in poor visibility is critical in providing individual driver assistance. Many studies (Brackstone et al., 2009; Brackstone et al., 2002, Brackstone and McDonald, 1999; Winsum, 1999) have focused on the concepts and theories of car following to understand drivers' car following behavior, their headway maintenance and how the choice of headway affects safety. However, literatures on car following behavior of drivers in fog are rare (Broughton et. al, 2007). Also, the available studies on drivers' behavior in fog utilize simulated data or driver survey data which are simplistic representation of real scenarios. In this context, the present study makes an effort to use real traffic data from Interstate 5 in California to study driver's car-following behavior by analyzing their choice of headway and speed in reduced visibility. In the following sections various relevant literature on car-following are documented followed by a methodology adopted in this study, results, discussion and conclusions.

RELAVANT LITERATURE

Drivers' behavior in car following has been studied extensively since 1950s and it is agreed upon that car following accidents occur due to inadequate time headways. While different countries have slightly different rules with regard to the legal headways (Vogel, 2003), on an average this recommended safety distances are close to 2 sec in good visibility conditions. In good visibility level a headway value of 50% of what is recommended, i.e. a value of 1sec could be unsafe. For example, Evans and Wasielewski (1982) found in a study of Michigan drivers that a headway of 1 sec or less is a major cause of accidents. There is also some evidence that in Sweden (Vogel, 2003) the police imposed fines to drivers with time headway of 1 sec. While there is some standard about the minimum acceptable headway in normal conditions, there is no guideline as to what would be the desirable headway in reduced visibility such as in fog, mainly because the rule would depend solely on the visibility level and a preset constant value is irrelevant. As a result, drivers drive according to their perceptions which may not always be safe.

The basic assumption of car following is that each driver should maintain a desired following headway behind the vehicle in-front. This is achieved by drivers by continuous adjustment of speed in prevailing traffic condition to ensure safety. This adjustment is influenced by drivers' perceptions of ground speed, proximity to their desired headway, and the dynamics of the relationship with the preceding vehicle as pointed by Brackstone & McDonald (1999). In reduced visibility, the dynamics of car following changes altogether since the following headways are not always chosen based on what drivers perceive as safe headway from a fear of losing reference. Hogema and Van der Horst (1995) reported decrease in following distance due to fog. They mentioned that the headways observed were too low for the driving speed in fog. Hawkins (1988) reported a marked increase in percent of short headway (less than 2 sec) distances when visibility fell below 150 m. Evans and Rothery (1976) and Evans (2004) reported that drivers' car following behavior is heavily influenced in dense fog due to obscure scenery and they attempt to follow a lead vehicle too closely for visible cues.

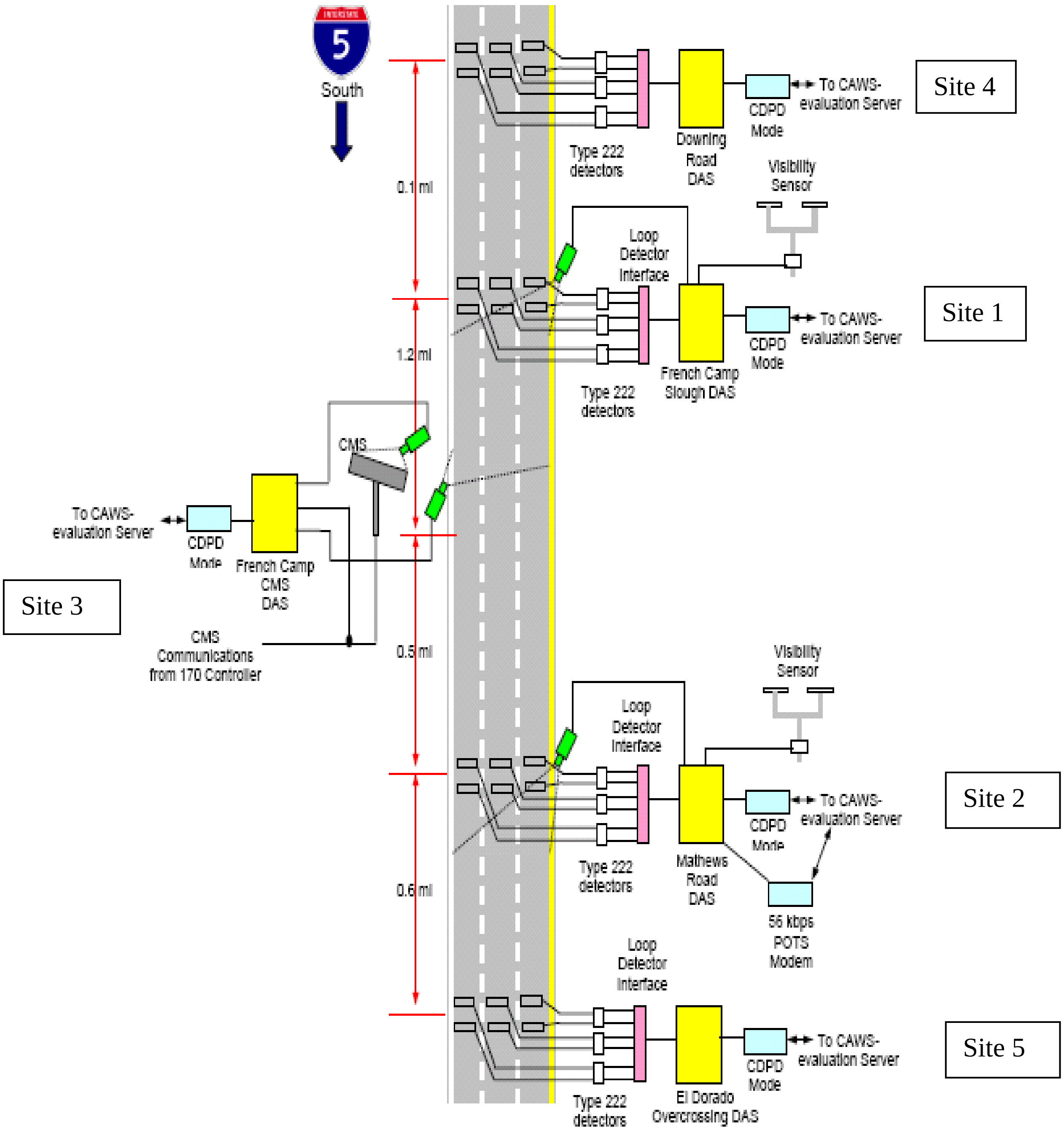
Similar observations are made by MacCarley et al. (2007) while studying driver conformance in dense fog along I-5 and SR120 in central valley of California. They noticed that drivers mean speeds were consistently above 60 mph, even in visibilities below 100 ft, when the advisory speed was 30 mph. These researchers calculated a new metric known as "Potential Collision Speed (PCS)" to predict the impact speed in a potential chain collision that considers visibility as well as the speed and separation between individual vehicles. They showed that in fog when the warning message was displayed in CMS the PCS increased by 10.17 mph compared to 0.36 mph when no message was displayed. These researchers also added that the PCS was found to decrease only 16.28 % of the times the message was displayed. Vogel (2003) studied "headways" and "Time to Collision (TTC)" and concluded that even though short headways leads to potential dangerous situations, TTC should be used to evaluate safety of a traffic environment since TTC takes into account headway as well as speeds of two consecutive vehicles. These observations from existing literature shows that in assessing safety in car following situation in general and in reduced visibility in particular, three parameters are of absolute importance—first, the headway or separation between vehicles; second, the speed of consecutive vehicles and third the available visibility distance if the visibility is not good. The important assumptions made are that all vehicles are in good performance and braking efficiencies are uniform across a specific type of vehicle.

Another important observation that can be made from literature review is that even though there are studies to estimate safety hazards of car following in fog by analyzing headways (Broughton et al., 2007) or estimating PCS in various visibility conditions, the findings are often not used as surrogate measures to detect dangerous driving conditions to caution drivers. As a result, even if we know drivers' choice of headways are often unsafe in fog and leads to very high PCS, the question is up to what minimum headway or separation would be good or safe for various leader-follower pairs in various visibility levels. Unless, we know such thresholds it will be difficult to detect dangerous drivers from the safe ones and it will also be difficult to get a clue of potential collision. In this context, the present study makes an effort towards developing a decision rule in which individual vehicle speeds, headways, PCS and TTCs are used as surrogate safety measures to detect potentially dangerous drivers who drive at very high speed compared to the separation and speed of the leader vehicle. Once such unsafe drivers are detected, it would be possible to guide such drivers through suitable Intelligent Transportation System (ITS) based measures such as Advanced Cruise Control (ACC) and Intelligent Speed Assistant (ISA) for better safety.

METHOD

The data for this study were collected from I-5 and SR-120 in central valley of California by MacCarley et al. (2007) as part of the CAWS evaluation study. The stretch of the highway where data collection was done is shown in Figure 1. There are four stations for data collection— two before and two after the CMS was placed. These stations are marked as site 4 and site 1 before CMS site, and site 2 and site 5 after CMS (refer Figure 1). In all of these sites i.e sites 1, 2, 4 and 5, traffic flow data collected by double loop detectors are studied to understand drivers' behavior in reduced visibility. A total of 12522 individual observations during evening peak periods of weekdays in the visibility range of 700-800 ft were analyzed in this study. The methodological steps followed in this study are given below.

FIGURE 1: Location of study site (Source MacCarley et al., 2007)



1. Initially, drivers' headways across sites and lanes are investigated. This is done by considering (a) the speed of the vehicles in car following and for (b) the overall condition without taking the speeds of the vehicles into account. From the first case, an idea of headway choice with respect to speed of car following is obtained, but to get an overall understanding of the driver's headway choice at the study site, cumulative distribution of headway is helpful. Based on the cumulative distribution diagram across sites and lanes, median (50^{th} percentile) and 85^{th} percentile headways are obtained. Based on these headways for different lanes and sites, conclusions may be made on whether the vehicles are in car-following or in free flowing state at the study location. For this purpose 6 sec headway value as suggested by Vogel (2002) is taken as threshold, such that only vehicles with headways of 6 sec or less are considered to be in car-following. However, it should also be noted that this threshold is recommended for vehicles in clear visibility and may vary with visibility level.

2. Once the vehicles in car following are identified, they may be divided in two groups. The first group of leader-follower are such that the followers have less than or equal to the speed of leader, whereas the second group of followers are the ones with higher speed than leaders. These are the drivers who are at risk if their separations are not adequate for their speed and visibility level. For these drivers TTC and PCS are needed to be estimated. Vogel (2003) defined TTC as the ratio of the separation between the two vehicles and their speed difference by. However, the calculation of TTC in the present case should take into account minimum of the separation or visibility as shown below in equation 1. Lower TTC values close to "0" indicate higher potential for crash and a larger TTC results in a lower likelihood of collision. After computing TTCs, vehicles with very low TTCs are identified and their trajectories are drawn.

   $$TTC = \frac{1}{V_f - V_l}\min(separation, visibility) \quad (1)$$

   Where, V_f = velocity of the following vehicle,
   V_l = velocity of the leading vehicle,

3. Since TTC depends both on speed difference of the vehicles in car following and the separation between them, distribution of speed difference is plotted for the vehicles having headway of 6 sec or less. Also, a cross classification table with TTC and headways for this location is also prepared. The TTC values may also be used to estimate risk of collisions by computing probabilities. For this purpose an exponential decay function as suggested by Oh and Kim (2010) and shown in equation 2 may be used. The changes in probability of collision with respect to the change in separation for various speed differences

are computed and a series of curves are plotted. These curves are useful in detecting possible collisions.

$$\Pr(Collision) = Exp(-TTC / c) \quad (2)$$

Where, c is a constant parameter to be estimated.

4. After the TTC and collision probabilities are estimated, PCS values also need to be computed. The basis for PCS calculation is similar to that of MacCarley et al. (2007), *except* that it is modified to take the relative speed of vehicles in car following (i.e. the speed difference as considered in TTC) as shown in equation 3. The main difference of this PCS formulation is that it takes the relative speed in car-following rather than the absolute speed of the follower and treats the leader as a fixed object. Based on the PCS values and referring a graph (Figure 2) developed by Richards (2010), it is also possible to determine the severity of the potential crash.

$$PCS = V_{fc} - V_l \quad (3)$$

Where

$$V_{fc} = \sqrt{V_f^2 - 2gk\left[\frac{V_1^2}{2gk} + \min(x_{sep}, x_{vis}) - V_f \times t_{react}\right]} \quad \text{if} \quad x_{sep/vis} \geq (V_{fc} - V_1) \times t_{react}$$

and

$$PCS = V_f - V_1 \qquad \text{if,} \quad x_{sep/vis} < (V_{fc} - V_1) \times t_{react}$$

Where,

V_{fc} = velocity of the following vehicle at the time of collision.

V_f = velocity of the following vehicle,

V_l = velocity of the leading vehicle,

t_{react} = reaction time,

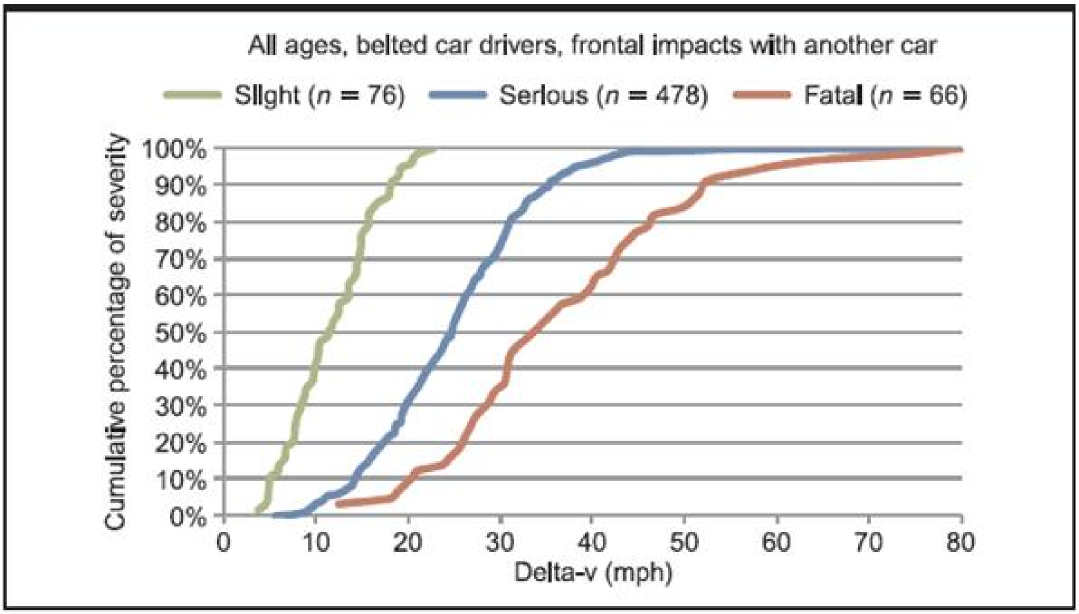
k = friction coefficient,

g = acceleration due to gravity.

x_{sep} = separation between vehicles car following

x_{vis} = available visibility between two vehicles

FIGURE 2: Severity of crashes with respect to relative speed of collision (Source: Richards, 2010)

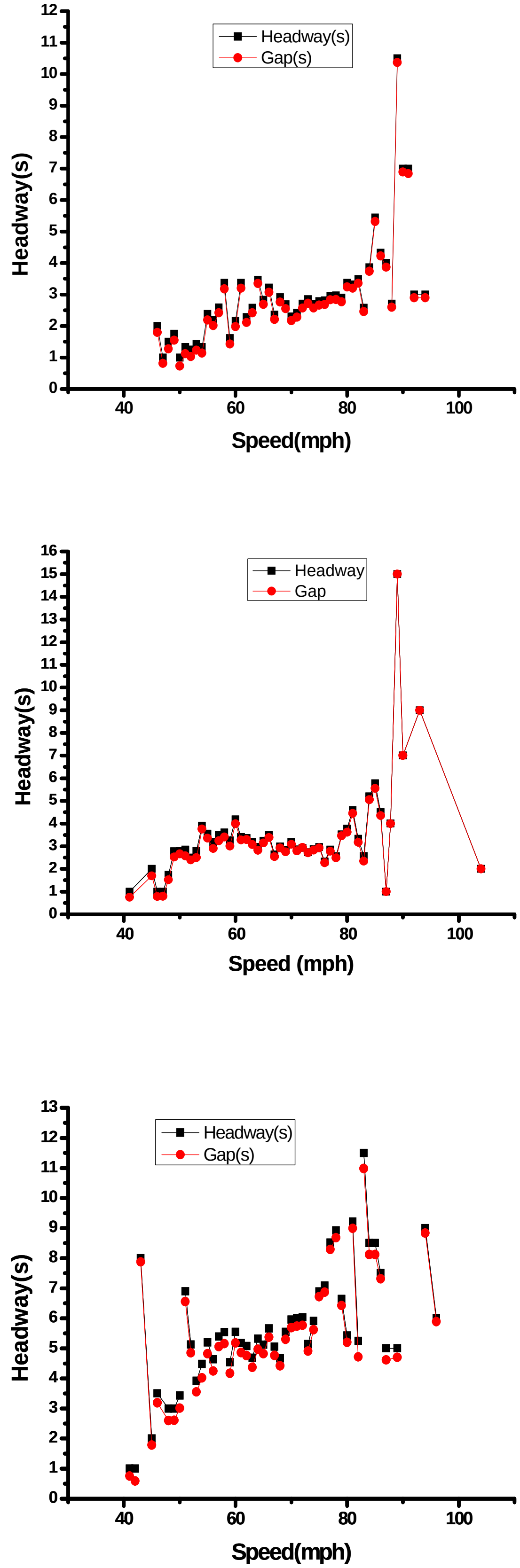


By following these steps and using 85th percentile headways, TTC and PCS as important surrogate measures, it will be possible to detect collisions. Then a back calculation may be done to guide drivers with a lower speed or higher separation to avoid a potential collision. These data may also be used in an exploratory manner to recommend suitable headways for the visibility condition. The results and findings from the analysis are discussed in the following section.

ANALYSIS AND DISCUSSION

Traffic data collected at all four stations of the site by duplex inductive loop detectors are stored in a central server. These individual vehicle records are used to calculate time of arrival (with a precession of 0.01 second), speed (up to 0.1 mph) and length of every vehicle in each of the three lanes. From the time of arrival, time headway is calculated. In this context it may be mentioned that "time headway" or just "headway" is defined as the elapsed time between the front of the lead vehicle's and the front of the following vehicle's reaching the same location, i.e. the difference in arrival time of two consecutive vehicle's front axle. On the other hand gap is a measure of elapsed time between rear bumper of the lead vehicle and front bumper of the following vehicle. In reality it is the gap or the physical separation that is of more importance than the actual time headway between two vehicles in car following in reduced visibility. Hence, while analyzing traffic data both headways and gaps are plotted with respect to speed across all sites in all three lanes. Sample plots from site 1 are shown in Figure 3.

FIGURE 3: Plot of headways with respect to Speed at Site 1 (lane 1, 2 and 3 from top)



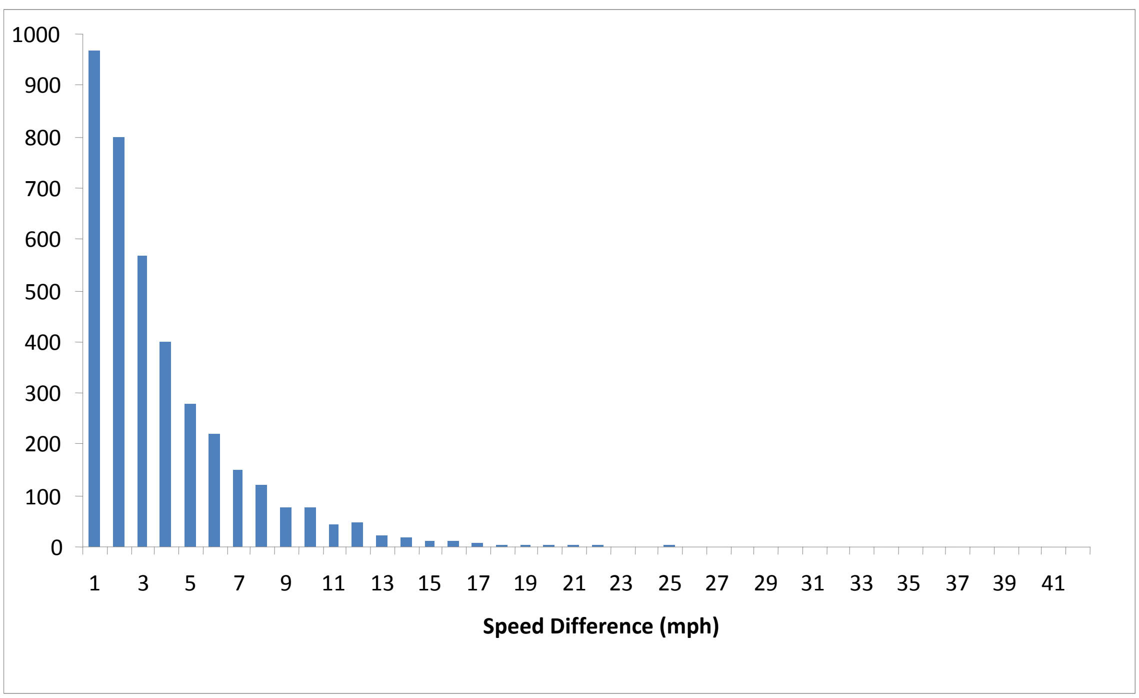
A closer look at these plots indicates that drivers tend to maintain a lower headway in lane 1 (fastest lane) compared to lane 2 and 3 (3 being the slowest lane) for a same speed. From these plots one can see the length of the vehicles and also observe that in lane 1 the differences between headways and gaps are very small compared to lanes 2 and 3, indicating the presence of longer vehicles in lanes 2 and 3 compared to lane 1. Except few outliers, the plots show a general trend of increased headways/gaps with speed across all lanes and stations. This finding is along the line of Kimbrough (2003), who showed that separating distance increases with increased initial speed of traffic while analyzing safe following distances under different road conditions. This observation is also as per expectation since braking distance increases with speed. In this study it is also observed that the choice of headways and gaps for a particular speed varies across lanes at all sites. It is found that drivers chose longer headways in lane 2 and 3 compared to lane 1. This again indicates that in right-most lanes, where the shares of heavy vehicles and slow moving vehicles are more, a general trend is to maintain longer headways. This confirms findings by Dey and Chandra (2009) who showed that the time headways maintained by cars are lesser than that of heavy vehicles and more so for slow moving vehicles in heterogeneous traffic flow. They also observed that the headways were the least for two-wheelers compared to all other categories of vehicles. Brackstone et al. (2009) investigated how the choices of headways depend on the types of lead vehicle and not the vehicle itself—which can not be directly compared to the observations from this study. While both headways and gaps are investigated at this stage, it is important to mention that headways are more reliable in this study than actual gaps since they are computed based on the vehicle lengths calculated using vehicle occupancy and certain calibration factors which depend on the sensitivity of the instrument. To get an idea of commonly adopted headways across different lanes and sites both 50th percentile and 85th percentile headways are checked. The summary of 50th and 85th percentile headways across sites and lanes are shown in Table 1.

TABLE 1: Site wise and lane wise 85th and 50th percentile headways

Site Id	Lane Id	85th%ile headway (s)	50th%ile headway (s)
1	1	4	1.5
1	2	4.5	2
1	3	7	3
2	1	4.5	1
2	2	5.3	2
2	3	11.2	4.5
4	1	4	1
4	2	4.5	2
4	3	7	3
5	1	4.5	1
5	2	5	2
5	3	9.5	4

50th percentile or median headways are in the range of 1 to 1.5 sec for lane 1; 2 sec for lane 2, and in the range of 3 to 4.5 sec for lane 3. When 85th percentile values are considered, the headways are obtained in the range of 4 to 4.5 sec, 4.5 to 5.3 sec and 7 to as high as 11.2 sec for lane 1, 2 and 3 respectively. From these observations it is clear that vehicles in lane 1 and 2 are in car following mode whereas vehicles in slow moving lanes may or may not be in car-following. Also, observations indicate that driver's headway choice may have been slightly influenced by the presence of the CMS, since for all lanes headways are in general higher at sites 2 and 5 (which are located after CMS) than at sites 1 and 4. For example, at site 1 and 4, at lane 1, the headways are observed to be 4 sec, but at site 2 and 5 for the same lane, the headways slightly increased to 4.5 sec. The increase, even though very small indicates that drivers on an average choose a higher headway after checking the CMS. However, this increase may not be safe enough for the driving condition, especially as can be seen on lanes 1 and 2. The increase in headway is as much as 2 sec to 4.2 sec in case of 3rd lane or slow moving lane, again showing a general trend that slow moving or heavy vehicles tend to select a higher headway than others. When speed difference between leaders and followers are examined (only for those observations in which followers have higher speed than leaders), it showed a half-normal distribution as shown in Figure 4.

FIGURE 4: Distribution of speed difference for the vehicles in car-following (only cases with higher following speeds than leaders are shown)



After that, only those vehicles with headways less than 6 sec are checked for TTCs based on the assumed threshold as mentioned earlier. Once the TTC are computed, a cross classification table is prepared to check distribution of TTCs with headways at the study location. Here the cross tabulation of TTCs up to 48 sec are shown in Table 2. A closer observation of Table 2 indicates that 95% of the TTCs fall between headways of 1 and 4 sec irrespective of the speed difference between the leaders and followers. Based on the cumulative distribution of headways obtained from Table 1, and the cross classification of headways from Table 2, a minimum headway of 4 sec may be recommended for the visibility level. This however, doesn't mean that any driver maintaining this headway will be able to avoid a collision no matter what is the driving speed. Rather this indicates that with a following headway of at least 4 sec in this particular visibility level, the driver will have enough reaction time to decide on his/her action. The TTCs may also be used to compute the probability of collision. However, the choice of c in equation 4 will influence the probability and it may only be estimated in the availability of real crash records from the study site. To show some of the obvious collisions, trajectories for six different cases are shown in Figure 5.

The next step was to compute PCS at the time of collision. For this purpose the expression of PCS as suggested by MacCarley et al (2007), was suitably modified it to take the effect of relative speed in car following. Based on the PCS and the graph developed in Richards (2010) it is possible to comment on the severity of the collision. It is also possible to back calculate the desired speed of the follower in car following from the PCS formula. However, one can see that the desired speed will be quite low for the follower if we want to make sure that the PCS must always be zero “0”. In other words, the separation required to result in a PCS of “0” will be very high. Hence, it is not efficient to suggest a headway from the requirement of PCS=0, as it will result in reduced capacity. On the other hand a visibility dependent safe following headway similar to what to suggest for clear visibility will be appropriate. Based on these considerations, a headway of 4 sec is thought to be ideal and is suggested from this study.

FIGURE 5: Trajectories of the selected vehicles showing possible collision

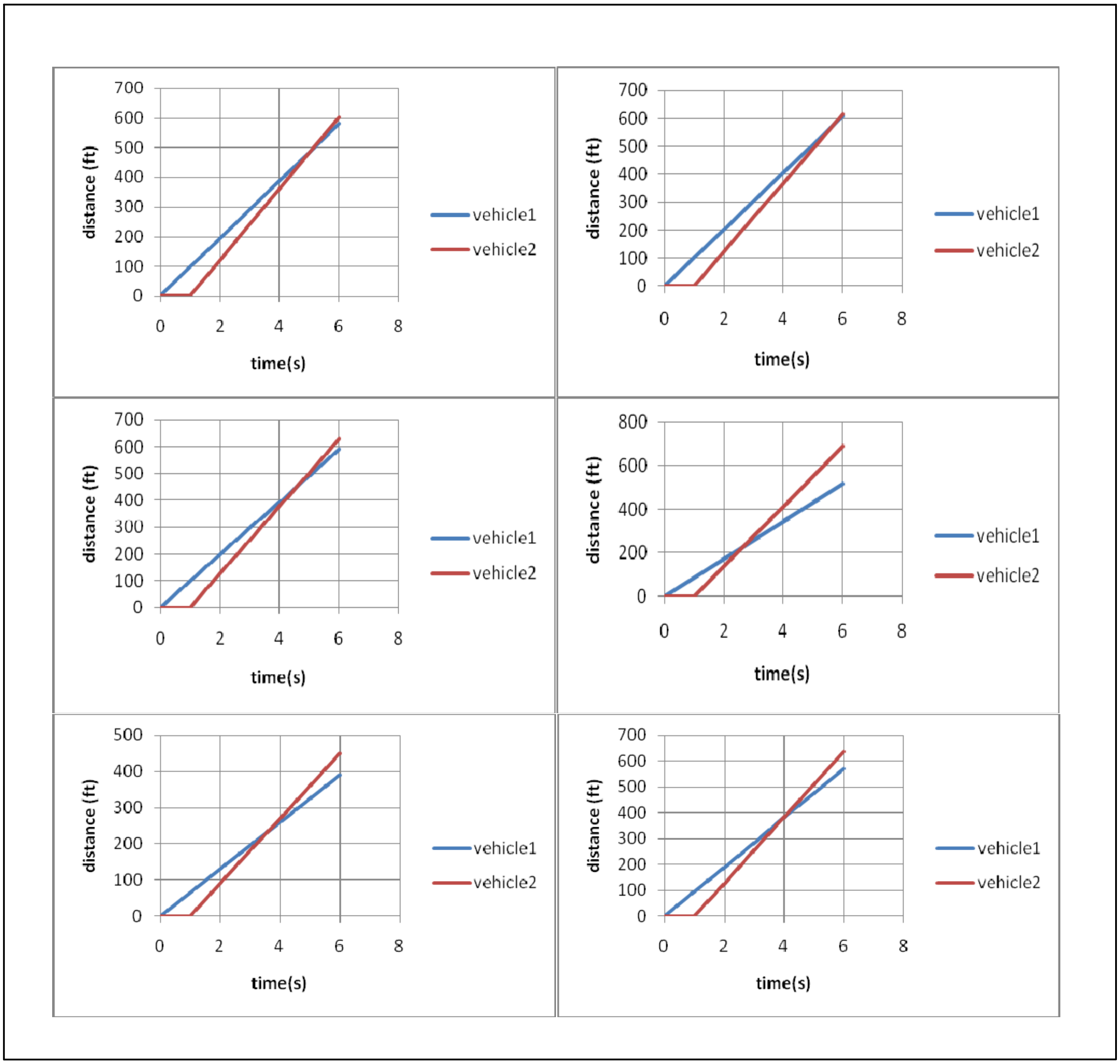


TABLE 2: Cross classification of TTC with headway

TTC	Total	Headway in Second(s)					
		1	2	3	4	5	6
1	2	2	0	0	0	0	0
2	2	2	0	0	0	0	0
3	3	3	0	0	0	0	0
4	3	3	0	0	0	0	0
5	9	8	1	0	0	0	0
6	14	14	0	0	0	0	0
7	19	19	0	0	0	0	0
8	25	22	3	0	0	0	0
9	27	19	6	2	0	0	0
10	29	19	9	1	0	0	0
11	51	40	11	0	0	0	0
12	54	39	11	3	1	0	0
13	71	53	14	4	0	0	0
14	62	45	13	2	0	2	0
15	77	49	21	6	1	0	0
16	59	38	13	6	1	1	0
17	56	35	19	2	0	0	0
18	66	30	24	11	1	0	0
19	57	32	18	2	2	2	1
20	70	41	10	16	3	0	0
21	76	32	24	13	4	1	2
22	57	32	17	3	3	1	1
23	52	18	16	8	7	3	0
24	51	14	24	7	5	0	1
25	42	15	13	8	3	3	0
26	50	15	15	11	6	2	1
27	60	24	17	6	12	1	0
28	75	32	25	13	3	2	0
29	74	41	14	7	9	1	2
30	100	74	12	8	2	3	1
31	71	49	7	7	3	4	1
32	91	57	19	6	5	3	1
33	64	33	13	10	3	4	1
34	44	12	16	7	5	2	2
35	35	8	14	6	3	4	0
36	30	0	13	8	4	4	1
37	33	4	13	7	7	1	1
38	33	1	11	11	3	5	2
39	21	1	5	4	8	1	2
40	23	0	12	8	1	1	1
41	26	0	15	4	1	5	1
42	26	1	14	2	7	1	1
43	30	0	17	8	1	4	0
44	27	1	11	5	4	3	3
45	33	2	23	1	4	1	2
46	27	3	13	5	4	1	1
47	35	4	17	8	2	2	2
48	25	8	7	5	3	1	1

CONCLUSIONS AND FUTURE SCOPE OF WORK

Car-following in fog is studied in this research by analyzing drivers' speed and headway maintenance in reduced visibility. In general following headways increased with speed, however, the increase is not enough to avoid potential collision. Major conclusions from this study are:

- Drivers' car-following behavior in the fast lane and the middle lane is not affected by drop in visibility since evidence shows that half of the drivers on those lanes chose headways as low as 1 sec. In addition, almost all drivers in those two lanes were found to be in car following mode with headways less or equal to 6 sec.
- On the other hand, about 50% of the drivers on lane 3 are found to follow headways of at least 4 sec. Also, at least 15% drivers in lane 3 lagged behind their leaders and were not in car-following.
- Based on the observed headway data and the estimates of TTC, it is considered that a minimum headway of 4 sec would be appropriate for the visibility level.
- TTC and PCS are used as surrogate measures to detect potential collisions and its severity. However, the PCS approach taken earlier overestimated the PCS. So it is modified by taking the speed of the leading vehicle and by doing this, the following vehicle get a greater braking distance.
- This also results in a reduced PCS. Moreover, in reporting the final PCS, we considered the relative speed between the vehicles that are going to collide and not just the speed of the following vehicle as we believe relative speed is a much better measure of the severity of accident.

One of the findings from this study— the safe headway for the visibility level, is empirical in nature and needs to be confirmed with data from other locations. The TTC and PCS may be used to back calculate safe speed or separation in reduced visibility and may be used in intelligent speed assistance or headway assistance.

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