

# Development of a Novel Aerodynamic Solution to Mitigate Large Vibrations in Traffic Signal Structures

Final Report for NCHRP IDEA Project 201

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NCHRP IDEA 20-30/IDEA 201

# DEVELOPMENT OF A NOVEL AERODYNAMIC Solution to Mitigate Large Vibrations in Traffic Signal Structures

FINAL REPORT

**Prepared for** 

IDEA Program National Cooperative Highway Research Program Transportation Research Board

of

The National Academies of Sciences, Engineering, and Medicine

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#### **1. EXECUTIVE SUMMARY**

The cantilevered-arm traffic structures (e.g. structural supports of signs, luminaires, and traffic signals) are an integral part of the transportation systems. The cantilevered form of these structures, are prone to fatigue failures at the base of the cantilevered elements as there is no provisions for fatigue in that specification. This is attributable to the lack of consideration of fatigue in the design of these structures and to the wind environment that can induce galloping, vortex shedding, wind gusts, and truck-induced gusts. These structures' low mechanical damping (0.1-0.4%) is known to contribute to this type of behavior. While much research in recent years has been focused on development of vibration mitigation strategies or design of connections that are fatigue-rated, less attention has been given to the natural performance of these structures when exposed to the natural wind environment.

This project considers the "aerodynamic damping" as an active means to mitigate the large amplitude vibrations of these structures. The proposed method is superior to the other common approaches, as it uses the inherent characteristics of the traffic light (specific dimension ratios) to ensure that the aerodynamic damping is maximized during the gust events. It's unique in the sense that it will not require specific tuning (like those required for non-aerodynamic vibration mitigation systems), or implementation of the heavier fatigue-rated connections. The tests that were conducted in the Wind Simulation and Testing (WiST) Laboratory have shown that the proposed approach will help improve the performance of traffic signal structures. In these studies, tests on two different traffic light configurations were conducted. Then, physical characteristics of traffic lights was changed to reach the maximum possible aerodynamic damping at each instance. This in turn has resulted in rapid damping of the large amplitude motions. A traffic signal structure was then monitored in the field. The information collected from the field were then used to assess the impact of the traffic light modification on the response of the traffic light structure in in-plane and out-of-plane directions.

The implementation of the proposed dimensional characteristics in design of traffic lights and traffic signal structures is an excellent opportunity to address the longstanding issue of fatigue-related failures in these structures. The economic implications of this approach are huge considering the millions of these structures that are being maintained by cities and state DOTs. The implementation of the proposed strategy in design of the traffic lights and traffic signal structures will ensure longer life time for these structures while eliminating the costs associated with possible failures, the user costs imposed due to failures, and costs associated with the replacement. The proposed strategy is expected not to increase the fabrication costs of these structures. The proposed approach is expected to have a larger impact when the concept is extended to other traffic structures such as structural supports for signs and luminaires.

### **2. IDEA PRODUCT**

#### 2.1. BACKGROUND

Cantilevered mast-arm traffic signal structures are widely used as supports for traffic lights in the United States. These structures normally consist of a vertical pole and a horizontal mast arm, which is fixed to the upper part of the vertical pole, as shown in Figure 2.1.



FIGURE 2.1 Cantilevered mast-arm traffic signal structure

Generally, both the vertical pole and the mast arm have hollow circular cross-sections and tapered diameters, and they are made of galvanized steel. The attachments on the mast arm can vary and include different types and sizes of traffic lights, signs and detection equipment. The detail of the arm-to-pole connection is shown in Figure 2.2. The mast arm is welded at an arm base plate, and the arm base plate is bolted to another plate on the vertical pole.



Figure 2.2. Arm-to-pole connection

Wind may be a major source causing vibration of the mast arm. Due to the low mechanical damping and the large mass of the mast arm itself, it is highly susceptible to cyclic fatigue loading of the arm-to-pole connection, which could be large enough to cause fatigue damage on the structures. In the past 20 years, failures of cantilevered traffic signal structures have happened in many places in the United States. In the state of Missouri, a dozen traffic signal mast arms failed, most of which occurred after only one to two years in service (Wu et al. 2000). In Wyoming, a visual investigation was conducted, and over a third of the traffic signal structures had fatigue cracks at the arm-to-pole connection (Hamilton et al. 2000). In Texas, two fatigue failures were witnessed in the cities of Pflugerville and Lubbock (Florea et al. 2007). All these incidents created a need to study the wind-induced behavior and fatigue behavior of cantilevered traffic signal structures.

#### 2.2. STRUCTURAL ANALYSIS OF TRAFFIC SIGNAL STRUCTURES

Research has been done on cantilevered traffic signal structures to understand their structural dynamic properties. In Sinh et al. (2014), pluck tests were conducted on a cantilevered traffic structure with a 5.8 m vertical pole and a 25 m mast arm. The identified system frequencies of the first out-of-plane (horizontal) and in-plane (vertical) modes were 0.50 Hz and 0.53 Hz, respectively. From the free vibration response, the damping ratio of the first out-of-plane and in-plane modes were also identified, which were 0.62% and 0.28%, respectively. In Letchford and Cruzado (2008), a traffic signal structure with a 5.8 m vertical pole and a 13.4 m mast arm was chosen. The identified system frequency and damping ratio of the first out-of-plane mode was 0.89 Hz and 0.55%, respectively, and the first in-plane mode showed 0.98 Hz and 0.28%, respectively. Generally, the system frequencies of the first out-of-plane and in-plane mode is commonly larger than the first in-plane mode. This evidence could signify that in-plane vibration might not be good for cantilevered traffic signal structures, since the vibration in in-plane direction is more difficult to be damped out.

#### 2.3. WIND ENGINEERING OF TRAFFIC SIGNAL STRUCTURES

It is believed that wind force is the major source causing vibration of cantilevered traffic signal structures. There are four kinds of wind force that could induce vibration: wind gust, vortex-shedding force, galloping force, and truck-induced wind force. Vortex-shedding force is a result of vortices in the wake of an object that are shed from a bluff body and induce a fluctuating force in the across-flow direction that can lead to its vibration. It is known that vortex-induced vibration occurs at the largest amplitude when the shedding frequency of the vortices matches the natural frequency of a structure, and the wind speed at this point is called the lock-in velocity (Simiu & Scanlan, 1996). Galloping force mainly results from an asymmetric

structure shape. When a structure with such a shape begins to oscillate in the across-wind direction, the aerodynamic force on the structure tends exhibit increases motion and induce large-amplitude vibration called galloping vibration. Galloping vibration has been recognized as having a nearly constant frequency over a wide range of wind speeds and an amplitude that increases as a function of wind speed.

Wind force on cantilevered traffic signal structures can be complicated. The attachments, such as traffic lights and sign plates, on the mast arm also play an important role in the effect that the different types of wind force can have on the structure.

In Pulipaka et al. (1995), wind tunnel tests were conducted on a scaled mast arm model with three scaled horizontal traffic lights. The test types included choosing wind direction from the front and the back of the traffic lights and different turbulence intensity of the wind. It was found that the wind from the back of the traffic lights can excite large across-wind vibration and the lower turbulence intensity can excite an even larger amplitude. Also, it was found that large across-wind vibration can only be excited in a specific wind speed region, which was verified as the vortex-shedding lock-in region. This test result shows a mast arm with horizontal traffic lights might experience large across-wind vibration due to vortex-shedding force.

In Zuo and Letchford (2010), a full-scale traffic signal structure with four attached horizontal traffic lights was monitored. The tip displacement of the mast arm, wind speed, and wind direction were recorded continuously. Through long-term observation, it was concluded that this type of traffic signal structure can experience large across-wind vibration at low wind speeds because of vortex-shedding force and is mainly vibrated in the along-wind direction by wind gust at high wind speeds.

In Kaczinski et al. (1998) and Van Dien (1995), wind tunnel tests were conducted to study the behavior of a cantilevered traffic signal structure with vertical traffic lights. Two scaled cantilevered traffic signal structure models were tested, one had a single scaled vertical traffic light and the other had no attachments. It was found that galloping-induced vibration can be excited on the model with the vertical traffic light while applying wind from the back of the traffic light. However, galloping-induced vibration was only observed once among many repetitive tests. Also, no vortex-induced vibration was observed on the wortex traffic light. On the model without any attachments, vortex-induced vibration was observed but no galloping-induced vibration. From this research, two conclusions may be possible. First, galloping force possibly excites a mast arm with vertical traffic lights. Second, because the attached vertical traffic lights create a non-uniform across-section along the mast arm, vortex-induced vibration might become difficult to excite.

In Chen et al. (2001) and Hartnagel and Barker (1999), a traffic signal structure with attached vertical traffic lights in Missouri was monitored to understand the effects natural wind gusts and truck-induced gusts have on the structure. Strain gauges were installed at the arm base to observe the strength of the gust. It was found that the stress at the arm base caused by truck-induced wind gusts is significantly lower than caused by natural wind gusts. It was also found that the amplitude of along-wind vibrations was three times larger than across-wind vibrations. Therefore, it was concluded that the vibration of this type of structure might be majorly caused by natural wind gusts instead of vortex-shedding force or galloping wind force.

#### 2.4. MOTIVATION AND PROJECT OBJECTIVES

There are a few factors that motivated the present research. First, most of the studies in the past were focused on cantilevered traffic signal structures with horizontal traffic lights. The reason could be due to the uniform cross-section along the mast arm, which makes it easier to create vortex-shedding force on the mast arm and more likely to observe large across-wind vibration. Cantilevered traffic signal structures with vertical traffic lights are also widely used today; however, there are fewer studies on them. Vertical traffic lights are suspected to have galloping instability (Kaczinski, Dexter, & Van Dien, 1998; Van Dien, 1995). Also, the mast arm of this type of traffic signal structure also has been observed to have large vibrations in either along-wind or across-wind directions. Thus, it is necessary to have a thorough investigation on cantilevered traffic signal structures have been reported to have fatigue damage on the arm-to-pole connection. It is necessary to seek a solution to reduce the vibration amplitude of the mast arm. Modifying the shape of traffic lights to increase their aerodynamic damping seems to be a possible and cost-efficient solution.

As to the motivations mentioned above, two objectives are addressed in the present research as follows:

- To have a thorough understanding of the wind-induced behavior of cantilevered traffic signal structures
- To demonstrate that the wind-induced vibration of a traffic signal structure can be reduced through the modification of the attached traffic lights

#### **3. CONCEPT AND INNOVATION**

Large amplitude vibration of traffic signal structures has been observed. The vibration of the mast arm can further cause fatigue failure of the pole-to-arm connection which also has been reported in many places.

Therefore, many studies have been conducted for developing vibration mitigation devices such as impact (Cook, Bloomquist, Richard, & Kalajian, 2001), viscous (Hamilton III, Riggs, & Puckett, 2000), and tunedmass dampers (Christenson & Hoque, 2011)to increase the fatigue life of these structures. However, only a few studies have been carried out using full-scale measurement or wind tunnel tests to explore the main source of vibration of these structures. Additionally, the developed vibration mitigation devices are limited in use based on the frequency bandwidth that require tuning from one structure to another.

This project considers the "aerodynamic damping" as an active means to mitigate the large amplitude vibrations of these structures. The proposed method is superior to the other common approaches, as it uses the inherent characteristics of the traffic light (specific dimension ratios) to ensure that the aerodynamic damping is maximized during the gust events. It is unique in the sense that it will not require specific tuning (like those required for vibration mitigation systems), or implementation of the heavier fatigue-rated connections.

In this project, traffic signal structure has been studied in many different approaches including wind tunnel test, field monitoring and analytical analysis to understand its wind-induced behavior and to demonstrate the performance of the proposed traffic light design. In wind tunnel test, the aerodynamic parameters of traffic light models and the mast arm section model were extracted which identify the potential types of wind forces on a traffic signal structure. Also, the modified traffic light was proven to have higher aerodynamic damping and lower drag coefficient than the original design. From the field observation, the wind-induced vibration in along-wind and across-wind directions was found to have a high correlation. Vortex-induced vibration was not observed frequently. The major types of wind forces on the monitored traffic signal structure were determined as drag and buffeting wind force and self-excited wind force. Drag and buffeting wind force comes from the wind pressure on the windward surface of the structure which applies in along-wind direction. Self-excited wind force comes from the aerodynamic stiffness of a structure. Based on the experimental and field observation results, an analytical model was built and successfully validated. The performance of the proposed modified traffic light design was evaluated from the simulated wind-induced response. The details of the investigation will be explained in Section 4.

#### 4. INVESTIGATION

#### **4.1. EXPERIMENTAL WORKS**

This section discusses the wind tunnel tests conducted on the reduced scale models of the mast arm section and different types of traffic lights to extract their aerodynamic and aeroelastic parameters in the Wind Simulation and Testing (WiST) Laboratory located at Iowa State University. These parameters will be used later to derive the analytical model and to further simulate the wind-induced response. The following sections explain the theoretical background, experiment procedures, and detailed results.

#### 4.1.1. Methodology

#### Aerodynamic Damping

Galloping instability of structures can be observed when aerodynamic damping becomes negative. Glauert-Den Hartog's criterion, shown in equation 4.1.1, determines the onset condition of galloping instability based on the quasi-steady theory for any type of structure (Blevins 1990, Den Hartog 1985).

$$\left(\frac{dC_L}{d\alpha} + C_D\right)\Big|_{\alpha=0} < 0 \tag{4.1.1}$$

where,  $C_D$  and  $C_L$  are drag and lift coefficients, respectively, of the structure, and  $\alpha$  is the vertical angle of attack of flow with respect to relative velocity. Figure 4.1.1 describes the velocity components, angle of attack ( $\alpha$ ), and aerodynamic forces of drag ( $F_D(\alpha)$ ), and lift ( $F_L(\alpha)$ ) acting on a traffic light.



FIGURE 4.1.1. Drag and lift forces acting on a traffic light

The aerodynamic damping ratio ( $\zeta_h^{aero}$ ), used to explain the vibration of a traffic light in the acrosswind direction, can be calculated by finding the components of  $F_D(\alpha)$  and  $F_L(\alpha)$ , given by equation 4.1.2.

$$\zeta_h^{aero} = \frac{\rho UD}{4m_h \omega_h} \left( \frac{dC_L}{d\alpha} + C_D \right) \tag{4.1.2}$$

where,  $\rho$  is air density, U is mean wind speed, D is across-wind backplate length,  $m_h$  is generalized mass per unit length, and  $\omega_h$  is circular frequency.

#### 4.1.2. Experimental Setup

In this study, all experiments were performed in the Aerodynamic/Atmospheric Boundary Layer (AABL) Wind and Gust Tunnel (2.44 m W×1.83 m H) located at Iowa State University (Jafari, Sarkar, & Alipour, 2019). A new setup was built to measure aerodynamic/aeroelastic loads and pressure distributions for static and dynamic wind tunnel tests of the section models. This setup, also capable of testing two models in tandem, properly secures the section model for yaw angles in the range of 0° to 45°. Figure 4.1.3 shows a wind tunnel test section and the static and 1DOF dynamic setup. The calculated blockage ratio was less than 5% for all experiments (Jafari et al., 2019).



FIGURE 4.1.3. Wind tunnel test section and experimental setup

#### Traffic Light Model

Since traffic lights may have different positions and configurations, static experiments were performed for vertical position (VP) and horizontal position (HP), and for front configuration (FC) and back configuration (BC) representing the wind direction with respect to the traffic light (see Figure 4.1.4). The angle of attack (AOA) defined for the traffic light is shown in Figure 4.1.4.





FIGURE 4.1.4. Definition of angle of attack, positions, and configurations of traffic light

Since past studies have shown that yaw angle has a significant effect on traffic signal structure vibration, the effect of yaw angle and angle of attack defined in Figure 4.1.5 were investigated using the static setup.



FIGURE 4.1.5. Traffic signal structure and dimensions of traffic light model with a scale of 1/4.2

As required by the tests on different yaw angle and angle of attack, two scaled traffic light models were used. The dimensions of the smaller traffic light model with a geometric scale of 1/4.2 are shown in Figure 4.1.5. This model was used for all static and dynamic tests except the vortex-shedding tests that required a larger but lighter model. The second model, with a geometric scale of 1/1.7 and displayed in Figure 4.1.6, was used to extract the vortex-shedding properties of a traffic light.



#### FIGURE 4.1.6. Vortex-shedding setup (vertical-1DOF) of traffic light model with a scale of 1/1.7

Table 4.1.2 summarizes the properties of the dynamic setup and the two scaled traffic lights for different positions.

Parameters	Scale 1	Scale 1/1.7	
	Horizontal pos. (HP)	Vertical pos. (VP)	Horizontal pos. (HP)
Diameter (D)	140 mm	440 mm	349 mm
Length (L)	440 mm	140 mm	1095 mm
Mass (M)	3.6 kg	3.6 kg	5.5 kg
Damping ratio ( $\zeta$ )	0.0022	0.0032	0.0152
Natural frequency ( <i>n</i> )	2.22 Hz	2.22 Hz	4.39 Hz
Stiffness (k)	840 (N/m)	840 (N/m)	4,200 (N/m)
Scruton number	0.75	0.35	0.51
$(Sc = M\zeta/L\rho D^2)$	0.10		0.01

#### TABLE 4.1.2. Properties of two scaled traffic lights

To represent a free vibration system, eight springs and two air bearings were used to capture the displacement of the section model using two load cells. Details related to data acquisition will be explained later.

#### Mast Arm Model

Three circular cylinders representing a section of the mast arm were used to conduct static and dynamic experiments as required by the specific tests. An aluminum polished tube with a diameter of 127 mm and of length of 1.52 m was used for static measurements. Although the aspect ratio (L/D = 12) was large

enough to prevent edge effects, two circular end plates with diameters of 4D were attached to both sides of the section model, parallel to the upstream airflow, to generate the 2D flow.

The model had 108 pressure taps distributed on its surface for measuring local pressures. There were 36 pressure taps at equal angular spacing of 10°, along each of the three rings located on the cylinder and spaced 4D or 5D distance apart. As shown in Figure 4.1.7a, a circular cylinder with diameter of 102 mm and length of 1.52 m was used to extract the flutter derivatives of a free vibration system for which the total mass was 3.6 kg, the total stiffness was 560 N/m, the natural frequency was 1.99 Hz, the damping ratio was 0.0041, and the Scruton number was 0.77.



(a) Free vibration dynamic setup

(b) Buffeting setup



For the buffeting tests, an aluminum polished tube with a diameter of 127 mm and length of 0.61 m was used to measure the admittance functions associated with buffeting loads along vertical and lateral directions at different yaw angles. The aspect ratio (L/D = 4.8) of the section model used for buffeting tests was kept larger than the correlation length  $(L/D \approx 4)$  of the wind loads along the model length. Figure 4.1.7b shows the section model with a gust generator fixed upstream of the model to generate a sinusoidal gust at a fixed frequency and uniform amplitude over the model's length. The wind upstream of the gust generator was uniform and smooth. The gust generator (two thin plates in parallel with a gap) was supported by a frame and connected to a motor by a rod that enabled it to oscillate at a specific frequency and amplitude. A load cell (JR3) was fixed on each side of the model for measuring the loads. The upstream wind speed of the model was recorded by a velocity probe (Cobra Probe, Turbulent Flow Instrumentation) located 20 cm downstream of the gust generator.

Data Acquisition System

Aeroelastic static loads were measured for the traffic light or mast arm model by the two force balances (JR3) shown in Figure 4.1.8a.



(a) Force balance (one end)



(b) Dynamic system (one end)

FIGURE 4.1.8. Data acquisition device for static and dynamic measurements

As shown in Figure 4.1.8a, both JR3s that were perpendicularly attached to both sides of the model recorded the three components of force generated by the wind. The drag coefficient ( $C_D$ ) and lift coefficient ( $C_L$ ) were directly calculated based on the data collected by this system, where for force measurements, the sampling rate and sampling time were 500 Hz and 60 s, respectively, and a similar setup was used to measure the fluctuating loads in the buffeting tests. Surface pressure was measured on the circular cylinder to find the properties of the section model. For pressure measurement, two 64-channel pressure modules (Scanivalve ZOC 33/64 Px) were utilized with a sampling frequency of 250 Hz and a sampling time of 60 s. The dynamic system, including two air bearings, eight springs, and two load cells, is shown in Figure 4.1.8b.

LabVIEW software was used for data acquisition of two load cells attached on either side of the model, one on the top and one on the bottom. Final spring displacement data are the average from three repetitions of 60 s data recording collected from two load cells. These results are based on the average of three datasets to achieve more accurate data statistics.

#### **4.1.3. Experiment Results**

#### Static Aerodynamic Load of Traffic Light

Although traffic lights have different components such as hood, backside for lights, and backplate, the aerodynamics of a typical traffic light with a backplate with wind approaching from the back for normal wind is very similar to that of a flat plate. To demonstrate this, the aerodynamic coefficients of a flat plate

(infinitely long) are plotted in Figure 4.1.9 using equations 4.1.3 and 4.1.4, as given in the literature (Blevins 1990).



FIGURE 4.1.9. Aerodynamic coefficients of a flat plate

Figure 4.1.9 indicates that the slope of  $C_L$  is negative at  $\theta = 90^\circ$ . Hence, it shows that sections similar to a flat plate, e.g., a traffic light with the above plate, might have a negative aerodynamic damping at  $\theta = 90^\circ$ , requiring measurement of its aerodynamic coefficients.

$$C_L = C_N \cos(\theta) \tag{4.1.3}$$

$$C_D = C_N \sin(\theta) \tag{4.1.4}$$

where,

$$C_N \approx \begin{cases} 2\pi \tan(\theta) & \theta < 8^{\circ} \\ 0.8 & 8^{\circ} \le \theta < 12^{\circ} \\ \frac{1}{0.222 + \frac{0.283}{\sin(\theta)}} & 12^{\circ} \le \theta < 90^{\circ} \end{cases}$$

Since variations of drag and lift coefficients with respect to angle of attack are needed to calculate the aerodynamic damping given by equation 4.1.2,  $C_D (= \frac{F_p}{0.5\rho U^2 DL})$  and  $C_L (= \frac{F_h}{0.5\rho U^2 DL})$  of the traffic light at different positions (HP and VP) and configurations (FC and BC) are plotted in Figure 4.1.10 as measured in the static wind tunnel tests for different angles of attack ( $\alpha$ ) and Reynolds numbers ( $Re = \frac{\rho UD}{\mu}$ ).





FIGURE 4.1.10. Aerodynamic coefficients of traffic light with a scale of 1/4.2 for different positions and configurations

As shown in Figure 4.1.10, the traffic light lift coefficient ( $C_L$ ) is plotted for angles of attack ( $\alpha$ ) ranging from -10° to +10° at different Reynolds numbers (Re); and the drag coefficient ( $C_D$ ) is plotted as a function of the Reynolds number for angles of attack ranging from -10° to +10°. Figure 4.1.10 indicates that the gradient ( $\frac{dC_L}{d\alpha}$ ) of  $C_L$  with respect to angle of attack is negative for all cases, while it is not a function of the Reynolds number in the studied range.

This negative slope, therefore, indicates that this structure can be vulnerable if aerodynamic damping becomes negative under special conditions. Furthermore, since the results for a yawed traffic light ( $\beta = 15^{\circ}$ ) show that the slope does not significantly change, experiments were not conducted for other yaw angles. The results for drag coefficient reveal drag reduction for a special range of Reynolds numbers, and this range is different for vertical and horizontal positions.

The quasi-static aerodynamic damping ratios of a full-scale five-unit traffic light were calculated using equation 4.1.2 to obtain static results for comparing the instability for different cases. The properties of this full-scale traffic light with a mast arm length of 18.28 m, previously studied by field measurement (Zuo and Letchford 2010), are provided in Table 4.1.3.

TABLE 4.1.3. Properties of full-scale traffic light for calculation of aerodynamic damping ratio

U <sub>WT</sub> (m/s)	rad		$D_{HP}, L_{VP}$	$D_{VP}, L_{HP}$
$(U_F/U_{WT}=1/4.2)$	$\omega_y(\underline{s})$	$m^*(kg)$	( <b>m</b> )	( <b>m</b> )
6 up to 30	6.28	307.3	0.58	1.83

Source: Zuo and Letchford 2010

The calculated aerodynamic damping ratios are summarized for different cases in Table 4.1.4.

$U_{WT}(\frac{m}{s})$	<i>Re</i> ×10 <sup>-5</sup>	C <sub>D</sub>	$\frac{dC_L}{d\alpha} _{\alpha=0}$	$\frac{dC_L}{d\alpha} _{\alpha=0} + C_D$	$\zeta_{aero}^{FS}(\%)$		
$\mathbf{H5}\text{-}\mathbf{BC}\ (\boldsymbol{\beta}=0^\circ)$							
5.79	0.54	1.36	-0.77	0.59	0.004		
9.77	0.91	1.31	-0.65	0.66	0.008		
12.24	1.14	1.33	-0.67	0.66	0.009		
17.29	1.61	1.33	-0.49	0.84	0.017		
22.33	2.08	1.33	-0.53	0.81	0.021		
24.91	2.32	1.34	-0.56	0.78	0.023		
27.49	2.56	1.34	-0.57	0.77	0.025		
30.06	2.80	1.33	-0.55	0.78	0.028		
		H5-F(	$C(\boldsymbol{\beta} = 0^\circ)$				
5.79	0.54	1.41	-0.18	1.23	0.009		
9.77	0.91	1.36	-0.14	1.22	0.014		
12.24	1.14	1.40	-0.195	1.21	0.018		
17.29	1.61	1.39	-0.17	1.23	0.026		
22.33	2.08	1.40	-0.13	1.27	0.034		
		H5-BC	$C(\beta = 15^{\circ})$				
5.79	0.52	1.29	-0.45	0.85	0.006		
9.77	0.87	1.16	-0.61	0.56	0.007		
12.24	1.09	1.20	-0.62	0.57	0.008		
17.29	1.56	1.26	-0.61	0.64	0.013		
22.33	2.01	1.30	-0.54	0.76	0.020		
		V5-B(	$C(\boldsymbol{\beta} = 0^\circ)$				
5.82	1.70	1.51	-1.21	0.30	0.021		

 TABLE 4.1.4. Summary of aerodynamic damping ratio for a full-scale traffic light

9.76	2.85	1.44	-1.19	0.25	0.029	
12.19	3.56	1.48	-1.21	0.26	0.038	
17.32	5.06	1.48	-1.20	0.28	0.058	
22.39	6.54	1.49	-1.13	0.36	0.097	
	$V5-FC (\beta = 0^{\circ})$					
5.82	1.70	1.55	-0.96	0.60	0.042	
9.76	2.85	1.48	-0.94	0.54	0.063	
12.19	3.56	1.52	-0.94	0.58	0.085	
17.32	5.06	1.52	-0.95	0.58	0.120	
22.39	6.54	1.53	-0.92	0.62	0.166	

To calculate the aerodynamic damping for the full-scale structure ( $\zeta_{aero}^{FS}$ ), the velocity scale for this set of experiments was considered as 1/4.2 ( $U_{\text{Field}}/U_{\text{Wind tunnel(WT)}} = 1/4.2$ ) by matching the Reynolds number. From the results presented in Table 4.1.4, the HP-BC case had the lowest aerodynamic damping, which confirms past results. Since it was found that a horizontal traffic light with back configuration (HP-BC) is the critical case with the lowest aerodynamic damping, all dynamic tests were performed for this case.

#### Static Aerodynamic Load of Mast Arm

The load cell (JR3) on one end of the mast arm model and the pressure taps on the model surface were both used to extract the drag coefficient of the mast arm model. The pressure data and the data from the load cell (JR3) were compared with each other to confirm the value of the drag coefficient. In Figure 4.1.11, the mean drag coefficient ( $C_D(\beta) = \frac{\overline{F_p}}{0.5\rho U^2 DL}$ ) of a circular cylinder is shown for different yaw angles over a range of Reynolds numbers.



FIGURE 4.1.11. Drag coefficient of a yawed circular cylinder at different Reynolds numbers

These results indicate that drag coefficient is reduced when yaw angle is increased. Since the drag coefficient of a yawed circular cylinder for  $0^{\circ} \le \beta \le 30^{\circ}$  was found to be nearly constant in a subcritical

Reynolds number range, the average drag coefficient is plotted for this range of yaw angles in Figure 4.1.11. In Figure 4.1.11b, the highest value of drag coefficient is plotted at  $\beta = 45^{\circ}$  case for a range of Reynolds numbers from  $5 \times 10^4$  to  $2.75 \times 10^5$ . An empirical equation (equation 4.1.5) using curve-fitting was proposed to predict the mean drag coefficient as a function of yaw angle while the factor of  $F(Re, \beta)$  was applied to consider the effects of yaw angle and Reynolds number for yaw angles larger than 30° due to variation in drag coefficient. It was assumed that the effect of yaw angle ranging from 30° to 45° is linear with respect to drag coefficient. The mean lift coefficient ( $C_L(\beta) = \frac{\overline{F_h}}{0.5\rho U^2 DL}$ ) was found to be zero for all yawed circular cylinders for  $0^{\circ} \le \beta \le 45^{\circ}$  in the subcritical Reynolds number range.

$$C_{D}(\beta) = C_{D}(0) \times (0.8\cos^{2}\beta + 0.2\cos\beta) \times F = (0.96\cos^{2}\beta + 0.24\cos\beta) \times F(Re,\beta^{\circ})$$
(4.1.5)  

$$F(Re,\beta^{\circ}) = \begin{cases} 1\\ 1.379 \times (1.778 \times 10^{8}Re^{-1.746} + 1) \times (-0.0125\beta^{\circ} + 1) \end{cases}$$
  

$$\begin{cases} 0^{\circ} \le \beta \le 30^{\circ}, 0.5 \times 10^{5} \le Re \le 2.2 \times 10^{5} \\ 30^{\circ} \le \beta \le 45^{\circ}, 0.7 \times 10^{5} \le Re \le 2.7 \times 10^{5} \end{cases}$$

#### Proposed Modification of Traffic Light

Since previous studies have shown that using a wing or horizontal flat plate increases the traffic signal structure aerodynamic damping (Pulipaka et al. 1998), a modified traffic light inspired by such a wing feature was designed for vertical and horizontal traffic lights. Figure 4.1.12 shows the vertical and horizontal traffic lights with attached aerodynamic dampers. The thickness of each aerodynamic damper is 0.1 in.



(b) Modified vertical traffic light

FIGURE 4.1.12. Designed aerodynamic dampers attached to traffic lights

The small gap between the flat plates and backplate allows air to flow freely through the gap. This gap not only allows the horizontal flat plate to work as an aerodynamic damper as intended but also helps to reduce the wake behind the backplate that leads to a reduction of the drag force on the traffic light. Furthermore, the dimensions and the locations of flat plates attached to the top and bottom of the traffic signal structure were designed in such a way that a motorist can easily see the traffic lights without disruption. Some of the advantages of the modified design of traffic lights with aerodynamic dampers include simple design, low manufacturing cost, easy assembly on existing traffic lights, and prevention of wind-induced vibration not only in the lock-in flow regime but also for all ranges of wind speed.

#### Self-Excited Load Parameters of Traffic Light

Flutter derivatives  $H_1^*$  and  $H_4^*$  of vertical and horizontal traffic lights (HP-BC and VP-BC) were extracted at various reduced velocities for a traffic light at  $\beta = 0^\circ$  both with an attached aerodynamic damper (modified) and without modification (original).  $H_1^*$  is related to aerodynamic damping in in-plane direction and  $H_4^*$  is related to aerodynamic stiffness in in-plane direction. In Figure 4.1.13, the results of flutter derivatives indicate that  $H_1^*$  has a lower absolute value for a horizontal traffic light (HP-BC), which translates to a lower aerodynamic damping compared to the vertical case (VP-BC) at a given reduced velocity (RV).



FIGURE 4.1.13. Flutter derivatives (1DOF-vertical) of original and modified traffic light for horizontal and vertical positions at  $\beta = 0^{\circ}$ 

Therefore, the dynamic results confirm that a horizontal traffic light is more unstable than a vertical one since it has lower aerodynamic damping. These results also prove that the modified traffic light configuration significantly adds the positive aerodynamic damping for both horizontal and vertical traffic lights over the entire range of wind speed.

#### Self-Excited Load Parameters of Mast Arm

Since the properties of a mast arm in lock-in regime below the wind speed of 9 m/s were desired, the flutter derivatives of a yawed circular cylinder were extracted for the across-wind direction using a free vibration system in a wind tunnel. Figure 4.1.14 shows the results for flutter derivatives that exhibit an increase in the lock-in regime at  $\beta = 45^{\circ}$ .



FIGURE 4.1.14. Flutter derivatives of yawed circular cylinder for different reduced velocities

#### Vortex-Shedding Force Parameters of Traffic Light

The Strouhal number for a yawed traffic light corresponding to different Reynolds numbers was estimated using point measurement of velocity in the wake. The Strouhal number results are plotted in Figure 4.1.15, and an empirical equation (equation 4.1.6) was found for predicting the Strouhal number of a traffic light at a given yaw angle.



FIGURE 4.1.15. Effect of yaw angle and Reynolds number on the Strouhal number of a traffic light

$$St(\beta^{\circ}) = -0.87\cos^{2}(\beta) + \cos(\beta) = St(0^{\circ}) * (-0.87\cos(\beta) + 1)$$
(4.1.6)

The aerodynamic damping parameters ( $Y_1$ ,  $\varepsilon$ ) for traffic light vortex-shedding load were needed to simulate the response of traffic signal structure; these were found for different yaw angles using equation 4.1.7.

$$\frac{h}{D} = \frac{2}{\sqrt{\varepsilon}} \left[ 1 - \frac{4\pi ScSt}{Y_1} \right]^{0.5}$$
(4.1.7)

The displacement (h) of the traffic light model with a scale 1/1.7 was recorded in the lock-in regime for two different Scruton numbers; then, the two equations were solved both at the specified Scruton number

and the Strouhal number at a given yaw angle to find the  $Y_1$ ,  $\varepsilon$ . The traffic light results for different yaw angles are given in Table 4.1.5.

β°	Y1	Е
0°	0.80	830
15°	0.95	560
30°	1.10	380
45°	1.20	150

 TABLE 4.1.5. Vortex-shedding properties of a traffic light model (HP-BC)

Vortex-Shedding Force Parameters of Mast Arm

The Strouhal number of yawed circular cylinders was measured to identify the lock-in wind speed for vortex-induced vibration of a yawed mast arm. In Figure 4.1.16, the Strouhal number, identified from the PSD of the lift coefficient, is plotted as a function of yaw angle in the subcritical Reynolds number regime, where it is constant at a given yaw angle.



FIGURE 4.1.16. Strouhal number as a function of yaw angle for circular cylinder

This shows that the Strouhal number reduces as yaw angle increases, and an empirical equation (equation 4.1.8) was obtained by fitting a curve to predict the Strouhal number of the mast arm at different yaw angles.

$$St(\beta) = St(0) \times \cos\beta = 0.2\cos\beta \tag{4.1.8}$$

In this study, the parameters for a vortex-shedding load of a circular cylinder ( $Y_1$ ,  $\varepsilon$ ) were used from results given in a past study (Gupta et al. 1996), where  $Y_1 = 10$  and  $\varepsilon = 300$ . It was assumed that these constants do not change for different yaw angles.

#### Buffeting Load Parameters of Traffic Light

The buffeting indicial derivative functions of the traffic light given as equation 4.1.14 and 4.1.15 were needed for time-domain simulation of wind loads acting on a traffic signal structure. For the vertical direction (h), it was conservatively assumed that the aerodynamic admittance function is equal to one  $(\chi^2(K) = 1)$ . Buffeting indicial derivative functions of a flat plate from literature (Chang et al. 2010) were used for the along-wind (p) direction, as given in equation 4.1.9.

$$\phi'_{p}(s) = 0.075e^{-0.513s} + 1.794e^{-2.111s}$$
(4.1.9)

#### Buffeting Load Parameters of Mast Arm

Since the buffeting indicial derivative functions were required to simulate the time-domain response of the traffic signal structure, they were extracted for a yawed circular cylinder using a gust generator. The PSDs of the upstream wind turbulence and aerodynamic loads were calculated to estimate the aerodynamic admittance functions at a fixed reduced frequency (K). The tests were repeated at varying wind speeds and different gust frequencies to cover the range of reduced frequency over which the aerodynamic admittance functions were desired. A LabVIEW program was developed to record the fluctuating aerodynamic loads (drag and lift) on the section model in the time domain, and the data was measured at a sampling frequency of 100 Hz. The results of aerodynamic admittance and buffeting indicial derivative functions for vertical and lateral directions at different yaw angles are shown in Table 4.1.6.

β°	<i>A</i> <sub>1</sub>	<i>A</i> <sub>2</sub>	<i>A</i> <sub>3</sub>	$A_4$
		$\phi'_h = A_1 e^{-A}$	$A^{2s} + A_3 e^{-A_4 s}$	
0	0.004	0.005	0.022	0.099
15	0.031	0.111	0.004	0.006
30	0.006	0.009	0.049	0.141
45	1.006	2.183	0.124	0.257
β°		$\phi'_p = A_1 e^{-A}$	$A^{2s} + A_3 e^{-A_4 s}$	
0	0.359	0.992	0.047	0.083
15	0.344	0.953	0.045	0.078
30	0.324	0.898	0.042	0.073
45	0.039	0.068	0.305	0.855

TABLE 4.1.6. Constants of buffeting indicial derivative function for a circular cylinder

For a traffic light, the buffeting indicial derivative functions of a flat plate were used for numerical simulation of traffic light from past studies (Chang et al. 2010).

#### **4.2. FIELD WORKS**

#### 4.2.1. Monitored Traffic Signal Structure

In order to observe the wind-induced behavior of traffic signal structures, a cantilevered traffic signal structure at Lincoln Way and University Boulevard in Ames, Iowa was selected for long-term monitoring. The selected traffic signal structure consists of a 7.62 m vertical pole, a 20.42 m curved mast arm, and three vertical traffic lights attached on the mast arm. The wall thickness of the pole and mast arm is 0.006 m. The tapered rate of diameter for the pole is 0.0117 m/m and is 0.0112m/m for the mast arm. Other dimension details are shown in Figure 4.2.1. The orientation of the selected structure is shown in Figure 4.2.2. Note that the three traffic lights face to the east.



FIGURE 4.2.1. Detail dimensions of the selected traffic signal structure



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#### FIGURE 4.2.2. Orientation of the selected traffic signal structure

#### 4.2.2. Sensor Installation and Data Acquisition

Sensors were installed on the selected traffic signal structure to monitor its wind-induced motion and record the wind data, which include accelerometer, strain gauge, and anemometer. For the accelerometer, a 3741B1210G from PCB Piezotronics, Inc. was used. It can only measure the acceleration in one direction. The measurement range is  $\pm 10$  g, the frequency range is 0 to 1,000 Hz, and the broadband resolution is 0.0012 g. For the anemometer, a MODEL 86000 from R. M. Young Co. was used. It can record both wind direction and wind speed. The maximum output update rate is 20 Hz. Wind direction is measured in degrees (0° ~ 360°), where 0° stands for north wind (wind from north blowing south), 90° is east wind, 180° is south wind and 270° is west wind. The resolution is 0.1°. Wind speed is measured in mph. The resolution is 0.022 mph. For the strain gauge, an HBW-35-125-6-25GP-NT from Hitec Products, Inc. was used. It can measure the strain in one direction. The strain is measured in micro-strain ( $\mu\epsilon$ ). The sensors and their placements are shown in Figure 4.2.3.





(b)

(c)

#### FIGURE 4.2.3. (a) Accelerometer, (b) strain gauge, and (c) anemometer

To record data from all the sensors in the same timeline, a data acquisition device, a CR5000 from Campbell Scientific, Inc., was used. All the sensors were connected to this device, and the data were saved in an external memory card put on the device. Considering the wind frequency and the structure frequency, the sampling rate was set to 20 Hz.

Several locations on the structure were monitored to evaluate the wind-induced vibration, which included the mast arm tip, the mast arm base, and the pole base. The sensor installation plan is shown in Figure 4.2.4.



FIGURE 4.2.4. Sensor installation plan

At the mast arm tip, two accelerometers were installed to monitor the acceleration in across-wind and along-wind directions, respectively. At the mast arm base, four strain gauges were installed at its top, bottom, east side, and west side to monitor the strain caused by vibrations. Also, the other two accelerometers were installed at the arm-to-pole connection to monitor the motion of the vertical pole. At the pole base, four strain gauges were installed at its north side, east side, south side, and west side to monitor the strain caused by vibrations. A 1.52 m long circular rod was attached at the tip of the vertical pole to provide a clean space for the anemometer. The anemometer was installed at the tip of the rod to monitor both wind speed and wind direction. Finally, the data acquisition device was placed in a metal box

attached near the base of the vertical pole. A hole was drilled at the bottom of the box to allow all the wires from the sensors to reach the data acquisition device.

#### 4.2.3. Pluck Tests and Results

Once the sensors were installed, pluck tests were conducted to understand the dynamic properties of the selected traffic signal structure. The test procedure is simply pulling the mast arm tip in either the out-of-plane (horizontal) direction or in-plane (vertical) direction and then releasing. The duration of each test is at least 1 minute to record a complete decaying process of the free vibration in both in-plane and out-of-plane directions.

In total, eight pluck tests were conducted. The first four times were in the in-plane direction, and the other four were in the out-of-plane direction. The acceleration record of the mast arm tip is shown in Figure 4.2.5, where the vertical dashed lines separate the data from each successive pluck test.



FIGURE 4.2.5. Acceleration record at the mast arm tip from pluck tests

In Figure 4.2.5, it can be seen that the damping ratio in the out-of-plane direction is obviously larger than the in-plane direction, since the free vibration damped out faster in the out-of-plane direction.

To more precisely understand the dynamic properties of the traffic signal structure, a system identification method called the Eigensystem realization algorithm (ERA) was used (Juang and Phan 2001). The motion of the structure was assumed as a linear system during small vibration, so it can be written as a linear state-space model, see equation 4.2.1. A, B, C, and D are the system matrices. With system input and output histories, the ERA is able to identify the system matrices. For the pluck tests, the system output is the free vibration response, and the system input is taken zero since there is negligible external force being applied to the structure from ambient wind. Also, in this case, the identified B matrix is the initial state, and the identified D matrix is the initial system output.

$$\dot{x} = Ax + Bu$$
  

$$y = Cx + Du$$
(4.2.1)

where, x is the system state, u is the system input, and y is the system output.

The system frequencies and corresponding damping ratios can be learned from the eigenvalues of the system matrix *A*. The system eigenvalues can be written as a complex form.

$$\lambda = a + bi \tag{4.2.2}$$

Then, the system frequency and corresponding damping ratio can be calculated as follows:

$$\omega_d = b, \omega_n = \sqrt{a^2 + b^2}, \xi = \sqrt{1 - \left(\frac{\omega_d}{\omega_n}\right)^2}$$
(4.2.3)

where,  $\omega_d$  is the damped frequency (rad/s),  $\omega_n$  is the natural frequency (rad/s), and  $\xi$  is the damping ratio.

Using the acceleration data shown in Figure 4.2.5, the identified frequencies and the corresponding damping ratios are shown in Table 4.2.1. The identified frequencies matched the frequencies determined by a spectral analysis in MATLAB. Also, to confirm the identified system matrices, the free vibration response was simulated by the identified system matrices and was compared to the field acceleration data. Figure 4.2.6 shows a good match of the acceleration data from the 1<sup>st</sup> pluck test and the simulated response.

Table 4.2.1. Identified natural frequency and damping ratio

Mode	1 <sup>st</sup>	2 <sup>nd</sup>	3 <sup>rd</sup>	4 <sup>th</sup>
Natural frequency (Hz)	0.531	0.597	2.060	2.118
Damping ratio (%)	1.604	0.315	0.592	0.110

The first mode is the out-of-plane motion, and the second mode is the in-plane motion. As shown in Table 3.1, the damping ratio of the out-of-plane first mode is much larger than the in-plane second mode.



FIGURE 4.2.6. Comparison of the acceleration data from the 1<sup>st</sup> pluck test and the simulated response

#### 4.2.4. Field Data Analysis

The traffic signal structure was monitored since April 2019. In this section, the field data for six months, from April 2019 to September 2019, was used to analyze the wind-induced behavior of the traffic signal structure. The 6 months of data were cut into segments, and each segment is 15 seconds. Therefore, wind statistical values such as 15 s mean wind speed and 15 s mean wind direction, and also the statistical values of the wind-induced response such as the maximum acceleration and the standard deviation of displacement at the mast arm tip were all calculated to see the interaction between wind and the structure.

The wind-induced behavior of the traffic signal structure can be analyzed in the out-of-plane and in-plane directions separately.

In the out-of-plane direction, Figure 4.2.7 shows the 15 s maximum acceleration at the mast arm tip against the 15 s mean wind speed in 8 wind directions.



FIGURE 4.2.7. 15 s maximum out-of-plane acceleration vs. 15 s mean wind speed

The range of each wind direction covers only 10°. Also, because it is difficult to discuss and summarize the wind-induced behavior when the wind is too turbulent, only the data points where turbulence intensity  $(I_u)$  was lower than 10% were selected. In Figure 4.2.7, the blue dots show the turbulence intensity is lower than 10%, and the red dots show the turbulence intensity is lower than 5%. Larger acceleration at the mast arm tip can present a larger vibration amplitude. In general, the out-of-plane vibration becomes larger as the wind speed increases, which can be observed in every wind direction. This might signify that the vibration in the out-of-plane direction is majorly affected by buffeting wind force that is induced by the drag force, which is proportional to the square of wind speed. Enough data points can show a clearer pattern. For example, in the northwest direction, the out-of-plane acceleration at the mast-arm tip against the 15 s mean wind direction for different range of 15 s mean wind speeds.

It can be seen that the wind from the back of the traffic lights  $(180^{\circ} \sim 360^{\circ})$  can excite larger outof-plane acceleration than the wind from the front, which can be observed in the wind speed range from 6.3 m/s to 8.0 m/s and from 8.9 m/s to 10.7 m/s. Also, the critical wind direction does not appear for the direction normal to the traffic lights (90° or 270°). The critical wind direction appears at around 135° and 315°, which can be observed at the wind speed range from 6.3 m/s to 7.2 m/s and from 8.9 m/s to 10.7 m/s.



FIGURE 4.2.8. 15 s maximum out-of-plane acceleration vs. 15 s mean wind direction



FIGURE 4.2.9. 15 s maximum in-plane acceleration vs. 15 s mean wind speed

In the in-plane direction, Figure 4.2.9 shows the 15 s maximum acceleration at the mast arm tip against 15 s mean wind speed.

Again, only the data points with a turbulence intensity lower than 10% were selected. In general, larger wind speeds can excite larger in-plane acceleration, which can be observed from all wind directions. In the west and northwest wind directions, low wind speeds of around 4.5 m/s to 8.9 m/s can excite relatively large in-plane acceleration. Vortex-shedding wind force can be excited when the vortex-shedding frequency matches the structural frequency. Therefore, vortex-induced vibration normally can only be observed in a specific wind speed range, which is called the lock-in region. Lock-in phenomenon can be observed at 4.5 m/s to 5.4 m/s in southeast, west and northwest wind directions. Among these three wind directions, northwest wind direction shows clearer lock-in phenomenon. However, the vortex-induced vibration did not happen frequently in the 3-month record. Therefore, the in-plane vibration might be majorly excited by buffeting wind force and self-excited force. Figure 4.2.10 shows the 15 s maximum in-plane acceleration against the 15 s mean wind direction.



FIGURE 4.2.10. 15 s maximum in-plane acceleration vs. 15 s mean wind direction

In Figure 4.2.10, several observations can be made. First, the highest in-plane acceleration appears with the wind from the back of the traffic light in all different wind speed ranges. Second, the critical wind direction is at around 315°, which can be observed at wind speeds from 5.4 m/s to 6.3 m/s when the

maximum acceleration exceeds 0.15g. In the wind speed range from 4.5 m/s to 11.6 m/s, there are enough data points in all wind directions, so it is reasonable to make this inference.

Figure 4.2.11 shows the 15 s maximum acceleration in both the out-of-plane and in-plane directions against the 15 s mean wind speed and 15 s mean wind direction.



FIGURE 4.2.11. 15 s maximum acceleration vs. 15 s mean wind speed and vs. 15 s mean wind direction

Based on all the data points (gray, blue and red dots), the monitored traffic signal structure had larger out-of-plane vibration than in-plane vibration. Most of the in-plane acceleration data are lower than 0.2 (g). There are many out-of-plane acceleration data larger than 0.2 (g). Also, when the wind is less turbulent ( $I_u \leq 10\%$ ), the wind-induced behavior in the out-of-plane and in-plane directions have a very similar pattern, which means the wind-induced vibration in the out-of-plane and in-plane directions have a high correlation. This might suggest that self-excited force could play an important role in wind-induced vibration, because there are displacement and velocity terms in both in-plane and out-of-plane directions in the equation of the self-excited force. The equation of the self-excited force will be explained in section 4.3.

#### **4.3. ANALYTICAL MODEL**

#### 4.3.1. Model Derivation

The analytical model of the selected traffic signal structure was built in order to simulate the wind-induced response and further to show the response improvement by modifying the traffic lights.

The analytical model includes three components, a vertical tapered pole, a curved mast arm, and three vertical traffic lights attached on the mast arm. The vertical pole is defined as a three-degree-of-freedom model, which has in-plane, out-of-plane, and twisting motions. The mast arm is defined as a two-degree-of-freedom model, which has in-plane and out-of-plane motions. The three traffic lights are modeled as a three-point mass attached on the mast arm.

Model derivation started with defining coordinate systems. The global coordinate  $(e_x, e_y, e_z)$  was set at the base of the vertical pole. Two body coordinates were defined at the pole base  $(e_x^p, e_y^p, e_z^p)$  and the arm base  $(e_x^a, e_y^a, e_z^a)$ , respectively, as shown in Figure 4.3.1.



FIGURE 4.3.1. Coordinate systems – 1

For the vertical pole, three generalized coordinates,  $w^p(x,t)$ ,  $v^p(x,t)$ , and  $\theta^p(x,t)$ , were defined to represent out-of-plane, in-plane, and twisting deformations, respectively. The body coordinate  $(e_x^{p^*}, e_y^{p^*}, e_z^{p^*})$  was defined along the neutral axis of the deformed pole. Also, the pole-to-arm connection was specified as  $(e_x^{c^*}, e_y^{c^*}, e_z^{c^*})$ . For the mast arm, two generalized coordinates,  $w^a(x, t)$  and  $v^a(x, t)$  were defined to represent out-of-plane and in-plane deformations, respectively. Similarly, the body coordinate  $(e_x^{a^*}, e_y^{a^*}, e_z^{a^*})$  was defined along the neutral axis of the deformed arm. The coordinate systems are shown in Figure 4.3.2.



FIGURE 4.3.2. Coordinate systems – 2

To determine the mode shapes, the finite element models of the vertical pole and the curved mast arm with three traffic lights were built separately in ANSYS. Mode shapes can be generated by conducting modal analysis, and shape functions were fitted by polynomial equations

#### 4.3.2. Damping Matrix

To include damping in the analytical model, a damping matrix needed to be designed. In Section 4.2, the damping ratios of each mode were identified through pluck tests and the system identification method. Based on the identified damping ratios, the damping matrix can be designed by superimposing the modal damping matrices, see equation 4.3.12.

$$C_{11\times11} = \sum_{i=1}^{n} \left(\frac{2\xi_i \omega_{n_i}}{M_{n_i}}\right) M \Phi_i \Phi_i^T M$$

$$M_{n_i} = \Phi_i^T M \Phi_i$$
(4.3.1)

where,  $\xi_i$  is the damping ratio,  $\omega_{n_i}$  is the natural frequency, and  $\Phi_i$  is the eigenvector of the i<sup>th</sup> mode.

In this study, the damping ratios of the first four modes were designed as the same as the identified damping ratios, and the damping ratios of the rest of the modes were assumed to be 0.5%. (Florea, Manuel, Frank, & Wood, 2007)

Thus, the damped system equation of motion of the traffic signal structure can be written as follows:

$$M_{11\times11}\ddot{q} + C_{11\times11}\dot{q} + K_{11\times11}q = 0 \tag{4.3.2}$$

#### 4.3.3. Wind Force Model and Generalized Force Matrix

As discussed in Section 2.3, several different wind forces can possibly excite traffic signal structures. In essence, drag and buffeting force and self-excited force always exist when wind acts on a structure. For a cantilevered traffic signal structure with attached horizontal traffic lights, vortex-shedding wind force is highly possible to excite at low wind speeds. For a cantilevered traffic signal structure with attached vertical traffic lights, vortex-shedding wind force was not observed in previous wind tunnel tests (Kaczinski et al., 1998; Van Dien, 1995). Also, although vertical traffic lights were suspected to have galloping instability, galloping-induced vibration was only observed once in previous wind tunnel tests (Kaczinski et al. 1998, Van Dien 1995).

Based on the observations in section 4.2, the monitored traffic signal structure also showed similar behavior. The monitored traffic signal structure did not frequently experience vortex-induced vibration at low wind speeds. Galloping instability also was not observed in high wind speeds. The vibration in out-of-plane and in-plane directions both become larger as the wind speed increased, and they seem to be highly related to each other. Based on all the evidence from the literature and field observation, two assumptions were made in this research. First, wind force is only applied on the mast arm and three traffic lights. Second, wind force types are considered to be drag and buffeting wind force and self-excited force on the mast arm and three traffic lights.

#### 4.3.4. Identification of Aerodynamic Coefficients

So far, the derivation procedures for the analytical model have been shown in previous subsections. However, in the analytical model, the aerodynamic coefficients such as drag coefficients and flutter derivatives are still unknowns. One way to identify the aerodynamic coefficients of the traffic signal structure is through wind tunnel tests. Thus, the aerodynamic coefficients of the mast arm section model and the traffic light model were tested to extract the aerodynamic coefficients. These identified parameters were then substituted in the analytical model. The analytical model applied the field wind data to simulate the wind-induced response. The wind-induced response was then compared with the field acceleration record to validate the analytical model. However, it turned out that the simulated response couldn't well match the field record. The simulated response tended to have larger amplitude than the field record. This might be due to the wind in the wind tunnel having much lower turbulence intensity than in reality, which created stronger wind force on the model. Also, the wind direction is slightly changing all the time in reality, and the aerodynamic coefficients might also be different in different wind directions.

Therefore, another method to identify the aerodynamic coefficients was adopted in this research. An optimization process was conducted to minimize the error between the simulated response and the field acceleration record. The parameters that needed to be optimized include the initial state of the analytical model and all the aerodynamic coefficients, which are drag coefficients of the mast arm and the traffic lights and the flutter derivatives of the mast arm and the traffic lights. The optimization process was implemented in MATLAB. The initial estimate of the parameters was selected as the identified result from the wind tunnel tests. The cost function is used as the mean squared error between the simulated response and the field acceleration record, see equation 4.3.19.

$$MSE = \frac{1}{n} \sum_{i=1}^{n} (Y_i - \hat{Y}_i)^2$$
(4.3.2)

where,  $Y_i$  is the simulated response, and  $\hat{Y}_i$  is the field acceleration record.

The optimization results and the validation of the analytical model are shown in section 4.3.5.

#### 4.3.5. Model Validation

The analytical model can be validated in two different aspects.

First, the dynamic properties of the analytical model were confirmed to match the result from the pluck tests. Table 4.3.1 indicates that the analytical model has system frequencies very close to the identified system frequencies.

	Mode	1st	$2^{\mathrm{nd}}$	3rd	4th
Analytical model	Natural frequency (Hz)	0.583	0.601	2.290	2.303
	Damping ratio (%)	1.604	0.315	0.592	0.110
Identified from	Natural frequency (Hz)	0.531	0.597	2.060	2.118
pluck tests	Damping ratio (%)	1.604	0.315	0.592	0.110

TABLE 4.3.1. Comparison of system frequency and damping ratio

Also, since the damping matrix of the analytical model was designed based on the identified damping ratios, the damping ratios of the analytical model are identical to the identified damping ratios.

Second, by applying the field wind data to the analytical model, the simulated acceleration response was confirmed to match the field acceleration record. The simulated response was generated by substituting the optimized aerodynamic parameters and initial states in the analytical model. The optimization procedure

was explained in Section 4.3.4. Table 4.3.2 shows the initial guess of the aerodynamic parameters and the optimal values.

	C <sub>D</sub>	<i>H</i> 1*	<i>H</i> 4*
Initial guess	1.2	-6.50	-1.70
Optimal value	0.4	-0.25	-1.64

TABLE 4.3.2. Initial guess and final optimal values of aerodynamic parameters

Two segments from the field records were selected to validate the analytical model. Figure 4.3.3 shows the first examination of the analytical model.



FIGURE 4.3.3. Result of the first examination: (a) wind direction, (b) wind speed, (c) out-of-plane acceleration, and (d) in-plane acceleration

The field data in Figure 4.3.3 was used to optimize both the initial states and the aerodynamic coefficients. Figure 4.3.4 shows the second examination of the analytical model.



FIGURE 4.3.4. Result of the second examination: (a) wind direction, (b) wind speed, (c) out-ofplane acceleration, and (d) in-plane acceleration

In Figure 4.3.4, the optimized aerodynamic coefficients from the first examination were used, and the initial states were optimized again to minimize the error. Both Figure 4.3.3 and 4.3.4 show the analytical model with the optimized parameters can accurately simulate the wind-induced response, which matches the field record. Two things can be inferred from the success of the validation of the analytical model. First, the modeling method used in this research is correct and accurate. Second, the simulated response is reliable, so the performance of the modified traffic light can be evaluated through changing the aerodynamic coefficients and observing the improvement from the simulated response. The study on the traffic light design will be explained in section 4.4.

#### 4.4. STUDY ON TRAFFIC LIGHT DESIGN

#### 4.4.1. Aerodynamic Coefficients of Traffic Light

Previous studies have shown that using a wing or horizontal flat plate can increase the aerodynamic damping and decrease the drag coefficient of the signal structures (Pulipaka et al. 1998). Therefore, in this study, the vertical traffic light was modified by adding wing features as shown in Figure 4.4.1 (Jafari et al., 2019).



FIGURE 4.4.1. Modified vertical traffic light

Wind tunnel tests were conducted on the original traffic light and the modified traffic light to identify their respective flutter derivatives (Jafari et al., 2019). The identified results are shown in Figure 4.4.2.



FIGURE 4.4.2. Identified flutter derivatives of the original traffic light and the modified traffic light

As shown in the equation of the self-excited wind force in section 4.3, flutter derivatives,  $P1^*$ ,  $P5^*$ ,  $H1^*$ , and  $H5^*$ , are related to aerodynamic damping. Larger aerodynamic damping means the structure can dissipate the wind-induced vibration faster. In Figure 4.4.2, the flutter derivative  $H1^*$  of the modified traffic light has larger negative value than the original traffic light, which means the aerodynamic damping in the in-plane direction of the modified traffic light is larger than the original traffic light. In section 4.4.2, the identified values are substituted in the analytical model to assess the performance of the modified traffic light.

#### 4.4.2. Performance of the Modified Traffic Light

All three vertical traffic lights in the analytical model were replaced by the modified traffic light, which meant the flutter derivatives and drag coefficient were replaced by the values of the modified traffic light. To evaluate the effectiveness of the modified traffic light, the damping ratios of the traffic signal structure with the original traffic lights and with the modified traffic lights were both calculated, see Table 4.4.1. Note that the damping ratio here includes the structural damping and aerodynamic damping, which is different from the damping ratios in Table 4.4.1. The 1<sup>st</sup> and the 3<sup>rd</sup> modes are related to out-of-plane motion. The 2<sup>nd</sup> and the 4<sup>th</sup> modes are related to in-plane motion. As shown in the table, the damping ratio of the 2<sup>nd</sup> and the 4<sup>th</sup> modes have increased from 0.4% to 4% and from 0.2% to 1.8% respectively.

	Mode	1st	2nd	3rd	4th
Original traffic	Natural frequency (Hz)	0.583	0.607	2.290	2.306
light	Damping ratio (%)	1.730	0.442	0.615	0.174
Modified traffic	Natural frequency (Hz)	0.583	0.607	2.290	2.304
light	Damping ratio (%)	1.730	4.000	0.615	1.817

 Table 4.4.1. Damping ratio of the traffic signal structure

The performance of the modified traffic light can also be evaluated from the simulated windinduced response. By applying the same wind data, Figure 4.4.3 shows the wind-induced displacement response at the tip of the mast arm.



FIGURE 4.4.3. Wind-induced responses of the traffic signal structure with original traffic lights and modified traffic lights

In the out-of-plane direction, due to the decrease of the drag coefficient, the amplitude of the outof-plane vibration had obvious reduction. In the in-plane direction, due to the increase of the aerodynamic damping, the in-plane vibration decayed much faster.

#### **5. PLANS FOR IMPLEMENTATION**

The proposed traffic light design has been proven to be able to effectively mitigate the vibration of traffic signal structures by wind tunnel tests and analytical simulations. As shown through the finite element models of the mitigated and unmitigated traffic light that was validated by the field data, the modified traffic light results in major reduction in the amplitude of vibrations (By almost a factor of two in both in- and out of plane directions). The unique aspect about this innovation is that by increasing the wind speed, the respective aerodynamic damping also increases, resulting in more degradation of amplitude of vibrations. The damage fraction functions at four locations of the mast arm base were established by the long-term monitoring data. These damage fraction functions show that majority of fatigue damage of the monitored traffic signal structure results from the wind-induced vibration in out-of-plane direction under lower wind speeds. However, the experimental tests show that galloping induced at higher wind ranges results in the higher damage.

In the implementation phase of the research, the team plans to use the traffic signal structure in a facility to install modified lights and monitor the performance of the light. This will serve the quick implementation of the proposed modifications in two distinct ways: 1) with the actual modified light exposed to wind and gust on a traffic signal, any uncertainty associated with the computational models will be removed and the team can estimate modified damage fraction functions, fatigue life and reliability. The results will then be presented to the AASHTO Committee on Structural Supports (T-12) that will help with the implementation of the results to the code. 2) with the monitored performance and data on site, the team will its industry partners will be able to receive the required approvals to fabricate the lights with new designs.

The team is planning to build a SLTS testing facility that would assist with the finalization of the product and making it ready for production in large quantities. For this purpose, a joint venture between Iowa State University, interested Cities, and interested fabricators will be formed. The team foresees four major steps for this purpose: (1) polishing the design of the modifications to the traffic light, (2) observation of the performance in full scale and field conditions in the SLTS testing facility, (3) market analysis through traffic structure fabricators and traffic light fabricators, (4) integration into code and product development.

From the inception of the project the team had engaged a major SLTS fabricator and three potential end users (from DOTs, cities, and companies) in the proof-of-concept phase. The team will also present the outcomes to the AASHTO T-12 as the code body to approve these changes. As part of the implementation phase, the team has secured the required matching funds for the Type 2 projects with a group of stake holders that highlights the interest in further implementation of this project. A group of the cities that manage hundreds of cantilevered traffic signals have presented the outcomes of the project in the American Public Works Association (APWA), it is expected that these dissemination efforts will further encourage the implementation of finally approved product in different jurisdictions.

#### 6. CONCLUSIONS

The wind-induced behavior of a cantilevered-arm traffic signal structure with vertical traffic lights was studied in this research.

With these promising results, implementation of the proposed dimensional characteristics in design of traffic lights and traffic signal structures is an excellent opportunity to address the longstanding issue of fatigue-related failures in traffic signal structures. The economic implications of this approach are huge considering the millions of these structures that are being maintained by cities and state DOTs. The implementation of the proposed strategy in design of the traffic lights and traffic signal structures will ensure longer life time for these structures while eliminating the costs associated with possible failures, the user costs imposed due to failures, and costs associated with the replacement. The proposed strategy is expected to decrease the fabrication costs of these structures. The proposed approach is expected to have a larger impact when the concept is extended to other traffic structures such as structural supports for luminaires and signs.

First, wind tunnel tests were conducted in the AABL Wind and Gust Tunnel located at Iowa State University. The tests included static and dynamic tests on section models of a circular cylinder representing a section of the tapered mast arm, and 1/4.2 and 1/1.7 scaled section models of traffic light units under uniform and smooth and/or gusty flow conditions over a range of yaw angles (0° to 45°) and wind speeds. The aerodynamic sectional properties and parameters for self-excited, vortex-shedding, and buffeting loads of circular cylinders and traffic light units were separately extracted from wind tunnel test data and used to numerically simulate the response of the traffic signal structure under both normal and yawed wind conditions for wind speeds ranging up to 9 m/s. From static experiments, drag and lift coefficients, and the Strouhal number were measured for a circular cylinder model and traffic light models. Also, their aerodynamic damping, stiffness parameters, flutter derivatives ( $H_1^*, H_4^*$ ), parameters for vortex-shedding loads were extracted at different reduced velocities. Aerodynamic coefficients of the mast arm section and the vertical traffic light model were later used in building the analytical model.

Second, a traffic signal structure was selected for long-term monitoring to understand the influence due to different wind speeds and wind directions. Pluck tests were conducted once the sensors were set up. System frequencies and corresponding damping ratios were identified from the pluck tests. It was found that the damping ratio of the out-of-plane first mode was five times larger than the in-plane second mode, which means the in-plane vibration is more difficult to be damped out. From the field data analysis, out-ofplane vibration was observed to become larger as the wind speed increases. It was found that the critical wind direction for out-of-plane vibration does not appear at the direction normal to the mast arm but at around 135° and 315°. From previous research, the vibration in the in-plane direction was suspected to be excited by vortex-shedding wind force or galloping wind force. From the field data, vortex-induced vibration did not happen frequently at low wind speeds, and also there's no galloping instability found in high wind speeds. This observation matches the results from previous wind tunnel tests on a traffic signal structure model with vertical traffic lights. By placing the data in out-of-plane and in-plane directions together, it was found that the wind-induced behavior in two directions had a high correlation. This might signify that self-excited force could play an important role in wind-induced vibration, because there are displacement and velocity terms in both in-plane and out-of-plane directions in the equation of the selfexcited force.

Third, a precise analytical model was derived to simulate the wind-induced response and to help further research on traffic light design. In total, 11 modes were included in the analytical model, which can at least describe the first four modes of the vibration in both in-plane and out-of-plane directions. The damping matrix was designed to have the system damping ratios be exactly the same as those identified from the pluck tests. The wind force model was considered as buffeting wind force, drag force, and selfexcited force. To validate the analytical model, the system frequencies and damping ratios were confirmed to match those identified from pluck tests. Also, the simulations were run with two different wind records, and the response can match the field record, which means the optimized parameters can work.

Finally, a new traffic light design has been proposed. It aimed to increase the aerodynamic damping of the traffic light and to reduce the vibration of the traffic signal structure. The new design added wing features such as flat plates along the height of the vertical traffic lights. Previous wind tunnel tests have shown that the new design can indeed reduce the drag coefficient and also increase the aerodynamic damping. After successful validation of the analytical model, the modeling method has proved to be correct, and the simulated response can be reliable. To evaluate the performance of the new traffic light design, the damping ratio was calculated before installing the modified traffic light and after. It was found that the new traffic light design can increase the in-plane damping ratio from 0.44% to 4.00%. Also, the simulated responses from the original design and the new design were compared to each other. The results showed the amplitude of out-of-plane vibration became smaller due to the decrease of the drag coefficient, and the in-plane vibration damped out significantly faster due to the increase of the aerodynamic damping.

#### 7. INVESTIGATOR PROFILE

Alice Alipour., Ph.D., P.E. is an Associate Professor in Department of Civil, Construction, and Environmental Engineering at Iowa State University with research experience in the investigation of civil infrastructure systems at both component and system levels. Her main research interests include development of resilience quantification strategies for infrastructure systems under extreme events, multi-hazard design and assessment of structures, decision-making algorithms for management of large-scale infrastructure systems, and post-disaster functionality assessment of complex networks. Her research is funded by multiple federal, state, and private organizations. She received the NSF CAREER award in 2018. Dr. Alipour has more than 90 scholarly papers published in prestigious journals and presented in national and international conferences. She is actively involved with multiple TRB and ASCE committees.

**Partha Sarkar, Ph.D.** is a Professor in the Departments of Aerospace Engineering at Iowa State University (ISU), USA since 2000. Before joining ISU. He is currently the Director of the Wind Simulation and Testing Laboratory. His main research interests and expertise are in wind engineering, fluid-structure interaction, and the

assessment of wind loads on the response of civil/aero structures, such as buildings, long-span bridges, cables, airplane wings, and wind turbine blades. His research has been funded by several federal agencies, state agencies and private industries. He has published 188 articles with about a third of those in journals and 4 patents on mitigation of wind loads and vibration. He has served on several ASCE national committees and he has led AAWE (American Association for Wind Engineering) as its president. He serves on editorial Boards of three journals.

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### APPENDIX



# Research Results

### Transportation Safety and Mobility May 2020 Project Title: **Development of a Novel** Aerodynamic Solution to Mitigate Large Vibration in **Traffic Signal Structures** PI: Alice Alipour, Ph.D., P.E. Associate Professor Department of Civil, Construction and **Environmental Engineering** Iowa State University

# **Development of a Novel** Aerodynamic Solution to Mitigate Large Vibration in **Traffic Signal Structures**

Modified traffic light has been proved to be able to effectively mitigate the vibration in traffic signal structures

#### WHAT WAS THE NEED?

Cantilevered traffic signal structures are widely used as supports for traffic signals in the United States. Many instance of the failures of cantilevered traffic signal structures have been reported in the past. This is attributed to the large amplitude vibrations that are caused by galloping, vortex shedding, natural wind gusts and truck-induced gusts. The reason for large amplitude vibrations is the low mechanical damping (0.1-0.4%) in these structures.

There is a need to develop innovative methodologies to overcome this issue.

#### WHAT WAS OUR GOAL?

Use "aerodynamic damping" as an active means to mitigate the large amplitude vibrations





Horizontal and vertical modified traffic light models

# IOWA STATE **UNIVERSITY**



Development of a Novel Aerodynamic Solution to Mitigate Large Vibration in Traffic Signal Structures



#### WHAT DID WE DO?

- 1. Wind tunnel tests were conducted on traffic light models and mast arm model to extract the aerodynamic and aeroelastic coefficients for the base model and the modified models.
- A traffic signal structure in Ames, Iowa was selected for long-term monitoring. Field measurements for mast arm vibration in alongwind and across-wind directions were analyzed to understand critical wind speed, critical wind direction and the major types of wind forces on the structure.
- An analytical model of the monitored traffic signal structure was generated and validated by comparing the simulated response and field measurements. The comparison of simulated wind-induced responses showed the performance of the modified traffic light was superior to the regular signal light.



#### WHAT WAS THE OUTCOME?

Aerodynamic and aeroelastic coefficients of the traffic light models and mast arm model were identified through wind tunnel tests. It was found that comparing with the original traffic light model, the modified signal light model has a higher value of the flutter derivative related to aerodynamic damping and a lower drag coefficient. From the analysis of the field measurement data, the vibration of a cantilevered traffic signal structure with vertical signal lights might be majorly induced by drag and buffeting wind force and self-excited force. Through the simulated wind-induced response, the modified traffic light proved to be more efficient in reducing the amplitude of along-wind vibration.

#### WHAT IS THE BENEFIT?

- The proposed modification will use wind to mitigate wind excitations.
- This is the first known effort to use the geometric characteristics of the signal light itself to mitigate the problem.
- Since wind is used to mitigate wind-induced vibrations, it will be able to mitigate the vibrations due to any type of winds (synoptic or nonsynoptic).
- No need to tuning, adding mass or stiffness, or mechanical dampers. The system is designed such that it does not self excite and damps any excitations.
- Lower cost of fabrication (both material ad detailing) for the signal structures using the proposed technology is expected.
- Opportunity to rehabilitate the existing lights that have vibration problems with installation of modified signal lights.

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Location and orientation of the monitored traffic signal structure in Ames, Iowa

