National University of Singapore

DSC5104 - Introduction to Network Science & Analytics

Term Project Final Report

Fire response analysis in City of Boulder Colorado

Team 11

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Executive Summary

This paper studies the causal effect of a new road construction on the emergency response time of response units in Boulder, CO, USA using network data. An egocentric network was created with fire station and incident locations as nodes and each incident as an edge between the locations. Network features (degree, closeness), and incident specific features (emergency, distance, etc) were included in the difference-in-difference analysis. Results of the analysis shows that the construction of the underpass resulted in significant increase in response time of 32s during the construction and a significant decrease in response time of 41s after the construction is completed. It can be concluded that introducing new routes, be it for vehicles or pedestrians, could have a positive impact on response times due to improved connectivity and reduction in road congestion. It is recommended that cities that want to improve emergency response time can do so by introducing new routes in the city.

1. Introduction

1.1 Business Problem

According to National Fire Protection Association News and Research, a fire department in the United States responds to a fire every 24 seconds, although nearly every state across the nation shows a recent trend toward fewer fire deaths and lower fire death rates per million population as compared to 1980s. The rapid response of firefighters is critical to preserve life and protect property and this is a key aspect of public safety. Survival profiling shows that swift intervention makes a difference to whether someone lives or dies. With governmental budget cuts on public services being increasingly common, there is an increasing need to ensure that resources are well-utilized to maintain or even improve service standards.

1.2 Objective

This project studied the fire response network graph for the City of Boulder Colorado (CO) to understand what impacts response time to incidents so that it can be applied to minimise response time ensure efficient utilization of fire response resources. More specifically, the effect of a new road on the response time of incidences was studied. While this project is specific to Boulder CO, the concepts and methodology can be generalized to other cities around the world.

2. Dataset Descriptive Statistics

The fire unit response time dataset[1] contained 90,393 data points of 8 fire units' response time, which includes alarm handling, turnout and travel time, to all emergency incident locations in Boulder Colorado from a period of 01 Jan 2015 to 28 Mar 2019. The dataset was pre-processed to remove points with the following:

- Response time less than 10 seconds
- With no arrival time at the incident
- Vehicle turned back before reaching the incident location
- Emergency vehicles not dispatched from the fire station

Basic statistical analysis shows that the average response times of stations 1 to 7 are similar, at an average of 250 seconds with the exception for Station 8 (refer to Appendix A figure 2.1a & b). As station 8 is a training school for firefighters, it is only deployed in times of extremely high demand where other stations are engaged. Hence, the mean response time is much higher than the other

[1] obtained from http://data-boulder.opendata.arcgis.com/datasets/6ae16fc5d05b46189800f189a587a223_0

stations. The plots show that the distribution is skewed with a long tail for higher response time, indicating that there are instances that the emergency response was less effective.

Statistical analysis was done for winter vs other seasons, and peak vs non-peak. The seasonal analysis is to find out if snowfall affects response times. The mean response time in winter (258.6s) is lower than non-winter (268.6s), disproving the hypothesis. This could be due to the mild winter conditions with little snowfall in Boulder and lower likelihood of fire incidence in the winter. Analysis for peak and non-peak hours shows that mean response time does not differ significantly based on a t-test with significance 0.05. (Refer to Appendix A, figure 2.2a and 2.2b for boxplots of response time comparisons.) Hence, peak hours and seasonal conditions are not considered in the causality analysis.

3. Network Analysis

Using the location of the start and end point of each dispatch as nodes and dispatches as edges, the resulting network contains 4915 unique nodes and 6755 unique edges. From the analysis, the degree distribution of incident nodes is skewed towards degree of 1 (refer to appendix A figure 3.1). The overall graph network statistics are given in table 3.1.

Density	Diameter	Components	Clustering coefficient
0.0007606726	6	1	0

Table 3.1: Overall graph network statistics

Comparing node level statistics for each fire station, clustering and pagerank is close to 0, while closeness values are close between 0.2 to 0.4 as seen in table 3.2. Across stations, station 1 has the highest degree, followed by station 2 and 3. As all alters surrounds the 8 egos with no clustering, it is an approximate egocentric network. Refer to Appendix A, figure 3.2 and 3.3 for the network visualisation.

Station	1	2	3	4	5	6	7	8
Out-Degree	2053	882	1228	788	789	242	769	4
Closeness	0.462	0.379	0.400	0.373	0.373	0.345	0.372	0.318
Pagerank	0.148	0.053	0.073	0.060	0.058	0.019	0.048	0.000

Table 3.2: Network statistics of resulting network created

4. Causality Analysis

4.1 Baseline Road Underpass Project Background

An underpass was built at a section of baseline road (between Broadway (SH93) and 27th way) to address significant number of car accidents with cyclists and pedestrians. The construction began in May 2016 and was completed on 14 June 2017. The new underpass provided a safer crossing for cyclists and pedestrians which helped to reduce accidents at that area. By making that area less prone to accident, it improved connectivity and could lead to shorter travelling times for vehicles using that road[2].

In general, if improved road conditions and connectivity could lead to shorter travelling times, it may also lead to shorter travel response times by fire engines. As such it would be useful to analyse if the underpass project impacted travel times by fire engines using that road.

[2] https://bouldercolorado.gov/transportation/baseline-road-underpass

Based on geospatial plotting of fire stations to incident location (refer to figure 4.1), it can be deduced that all fire stations in City of Boulder mainly response to incident locations within 2 miles radius of its position. This finding is also aligned with City of Boulder web page, where it is stated that all addresses within City of Boulder limits are within 2 miles of a fire station.

Applying the same concept on the underpass project, it is initially assumed that fire stations 2 and 3, which lies within 2 miles radius of the road work (refer to figure 4.3), will be affected during and after the construction of this section of the underpass. Nevertheless, upon further investigation, the majority of fire station 3 respond routes did not pass through that particular section of the road (refer to figure 4.2), while for fire station 2, the underpass project was right outside the fire station and it can be assumed that majority of its routes need to pass through the road affected by the project. As such, only fire station 2 was considered in the treatment group, while the rest of the fire stations were considered as the control group.

4.2 Method of Analysis

Causal analysis was done using difference-in-difference (DID) method. DID studies the differential effect of a treatment on a 'treatment group' versus a 'control group' and calculates the effect of a treatment on an outcome by comparing the average change over time in the outcome variable for the treatment group, compared to the average change over time for the control group.

Difference-in-Difference (DID)

For the analysis, the full dataset is segmented into 3 sections, Before (Incidents happening before the start of construction, Before 1st May 2016), During (Incidents happening during the construction period, From 1st May 2016 to 15th June 2017) and After (Incidents happening after the completion of the underpass, From 16th June 2017 onwards).

Each dataset is further segmented into Control and Treatment group, where Station 2 is classified under Treatment and the rest of the stations as Control.

	Total Node (Locations)	**Total Edge (Responds)**	**Control Edge (Responds)**	**Treatment Edge (Responds)**
Before	2704	8294	7392	902
During	2557	7082	6621	461
After	1959	4616	3729	887

Table 4.2.1: Network attributes of response before, during and after construction

Network features including degree, closeness, betweeness and pagerank are derived for each node. Degree is the number of links connected to a node. It can be computed by summing the number of edges connected to it. Nodes with higher degree might have more influence on others and it can be used to either spread or stop the information. Closeness is the measurement of the average distance between a node and every other node in the network. Closeness can help to find the shortest path. Since the betweeness and pagerank for nodes were similar, these features were dropped for causal analysis.

Analysis was done based on the equation below using fire unit response time dataset and network features.

$$\underline{ResponseTime = \beta_0 + \beta_1(time) + \beta_2(tr) + \beta_3(time) * (tr) + \beta_4\, degree + \beta_5 closeness + \beta_6 distance + \beta_7 FHRESPONSECODE}$$

4.3 Interpretation

```
Call:
lm(formula = formula, data = data_BD)

Residuals:
     Min       1Q   Median       3Q      Max
-1255.05   -69.80   -26.63    29.85  3124.06

Coefficients:
                             Estimate Std. Error t value Pr(>|t|)
(Intercept)                113.072034  14.568190   7.762 8.91e-15 ***
time                         1.463135   2.593352   0.564  0.57264
tr                          -2.225461   5.359131  -0.415  0.67795
degree                      -5.884678   2.234373  -2.634  0.00845 **
closeness                   55.175827  53.931876   1.023  0.30629
distance1                    0.084950   0.001153  73.685  < 2e-16 ***
FHRESPONSECODENon Emergent  82.825581   2.554673  32.421  < 2e-16 ***
time:tr                     32.341658   8.964068   3.608  0.00031 ***
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Residual standard error: 150 on 15368 degrees of freedom
Multiple R-squared:  0.2945,	Adjusted R-squared:  0.2942
F-statistic: 916.6 on 7 and 15368 DF,  p-value: < 2.2e-16
```

Figure 4.4a: Baseline - Before and During

```
Call:
lm(formula = formula, data = data_AD)

Residuals:
   Min     1Q Median     3Q    Max
-322.6 -100.7  -36.9   46.1 3207.0

Coefficients:
                                     Estimate Std. Error t value Pr(>|t|)
(Intercept)                         2.278e+02  2.119e+01  10.750  < 2e-16 ***
time                                1.082e+01  3.960e+00   2.732 0.006308 **
tr                                  2.568e+01  9.449e+00   2.718 0.006575 **
degree                              2.231e+01  3.238e+00   6.889 5.89e-12 ***
closeness                          -7.148e+01  8.160e+01  -0.876 0.381043
distance1                           2.573e-06  1.704e-05   0.151 0.880021
FHRESPONSECODEEmergent - Downgraded 2.091e+01  3.026e+01   0.691 0.489658
FHRESPONSECODENon Emergent          7.314e+01  3.835e+00  19.073  < 2e-16 ***
time:tr                            -4.062e+01  1.188e+01  -3.418 0.000633 ***
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Residual standard error: 192.7 on 11689 degrees of freedom
Multiple R-squared:  0.04003,	Adjusted R-squared:  0.03937
F-statistic: 60.93 on 8 and 11689 DF,  p-value: < 2.2e-16
```

Figure 4.4b: Baseline - During and After

Results from the analysis (Figure 4.4a) showed that when comparing before the start and during the construction project, the response time of fire station 2 increased significantly, by 32 seconds, as compared to other fire stations not affected by the project. This is as expected as road construction would likely have negative impact on travelling times.

Results from the analysis (Figure 4.4b) also showed that when comparing during and after the completion of the construction project, the response time of fire station 2 decreased significantly, by about 41 seconds, as compared to other fire stations not affected by the project. This is also as expected since building a new underpass provide safer crossing for pedestrians resulting in lesser accidents and improved connectivity.

4.4 Robustness Test

Different robustness tests were performed to evaluate if the construction of the underpass actually affected the fire engine response time. The tests consisted of Propensity score matching (PSM), random assignment of treated and control group and placebo test.

Propensity Score Matching (PSM)

```
Call:
lm(formula = formula, data = data_BD_psm)

Residuals:
    Min      1Q  Median      3Q     Max
-542.88  -79.20  -30.01   28.70 2555.82

Coefficients:
                             Estimate Std. Error t value Pr(>|t|)
(Intercept)                  1.771612  42.755886   0.041 0.966952
time                         9.047786   9.369186   0.966 0.334282
tr                          -3.123394   8.606508  -0.363 0.716700
degree                     -25.740949   7.796607  -3.302 0.000974 ***
closeness                  498.650949 176.996231   2.817 0.004878 **
distance1                    0.088286   0.002968  29.747  < 2e-16 ***
FHRESPONSECODENon Emergent 101.899412   7.017104  14.522  < 2e-16 ***
time:tr                     33.039168  13.566620   2.435 0.014942 *
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Residual standard error: 170.6 on 2718 degrees of freedom
Multiple R-squared:  0.2827,	Adjusted R-squared:  0.2809
F-statistic: 153.1 on 7 and 2718 DF,  p-value: < 2.2e-16
```

Figure 4.5a: PSM - Before and During

```
Call:
lm(formula = formula, data = data_AD_psm)

Residuals:
    Min      1Q  Median      3Q     Max
-394.16  -82.32  -34.10   22.16 2550.04

Coefficients:
                                      Estimate Std. Error t value Pr(>|t|)
(Intercept)                         -36.135768  47.980345  -0.753 0.451434
time                                 -5.680649  10.576754  -0.537 0.591251
tr                                   26.878601  11.286582   2.381 0.017313 *
degree                              -27.989633   8.180470  -3.422 0.000632 ***
closeness                           657.539477 194.378805   3.383 0.000728 ***
distance1                             0.090105   0.003231  27.885  < 2e-16 ***
FHRESPONSECODEEmergent - Downgraded  -5.433682  37.462455  -0.145 0.884687
FHRESPONSECODENon Emergent          110.990302   8.451572  13.133  < 2e-16 ***
time:tr                             -32.663277  15.616352  -2.092 0.036567 *
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Residual standard error: 188.3 on 2687 degrees of freedom
Multiple R-squared:  0.2651,	Adjusted R-squared:  0.2629
F-statistic: 121.1 on 8 and 2687 DF,  p-value: < 2.2e-16
```

Figure 4.5b: PSM - During and After

To reduce the imbalance of data within control and treatment group, the propensity score matching technique was utilized to create control group with fire incident places similar to those under treatment group. Observations were selected based on propensity score matching with the treatment group. After replacing the original dataset with propensity matched dataset, the results are still statistically significant and coefficients were also comparable to baseline models (refer to Figure 4.5a & Figure 4.5b).

Random Assignment (RA)

```
Call:
lm(formula = formula, data = data_BD_random)

Residuals:
    Min      1Q  Median      3Q     Max 
-542.33  -78.83  -30.32   27.59 2581.30 

Coefficients:
                             Estimate Std. Error t value Pr(>|t|)    
(Intercept)                 15.656654  42.854983   0.365  0.71489    
time                        24.708475   9.732894   2.539  0.01118 *  
tr                          -5.937396   8.513778  -0.697  0.48562    
degree                     -23.081879   7.746893  -2.980  0.00291 ** 
closeness                  446.537345 175.991451   2.537  0.01123 *  
distance1                    0.087415   0.002949  29.643  < 2e-16 ***
FHRESPONSECODENon Emergent 101.266067   7.023192  14.419  < 2e-16 ***
time:tr                     -4.107474  13.326891  -0.308  0.75795    
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Residual standard error: 170.8 on 2718 degrees of freedom
Multiple R-squared:  0.281,	Adjusted R-squared:  0.2791 
F-statistic: 151.7 on 7 and 2718 DF,  p-value: < 2.2e-16
```

Figure 4.6a: RA - Before and During

```
Call:
lm(formula = formula, data = data_AD_random)

Residuals:
    Min      1Q  Median      3Q     Max 
-384.85  -81.85  -34.78   23.07 2563.58 

Coefficients:
                                      Estimate Std. Error t value Pr(>|t|)    
(Intercept)                          -6.586637  45.949557  -0.143  0.88603    
time                                -16.786007  10.582483  -1.586  0.11281    
tr                                   10.114425  10.559142   0.958  0.33821    
degree                              -23.063573   7.922536  -2.911  0.00363 ** 
closeness                           548.273131 187.962108   2.917  0.00356 ** 
distance1                             0.089439   0.003209  27.876  < 2e-16 ***
FHRESPONSECODEEmergent - Downgraded  -4.235534  37.376000  -0.113  0.90978    
FHRESPONSECODENon Emergent          111.156320   8.470096  13.123  < 2e-16 ***
time:tr                              -2.005013  14.562431  -0.138  0.89050    
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Residual standard error: 188.4 on 2687 degrees of freedom
Multiple R-squared:  0.2639,	Adjusted R-squared:  0.2617 
F-statistic: 120.4 on 8 and 2687 DF,  p-value: < 2.2e-16
```

Figure 4.6b: RA - During and After

Treatment dummy was randomly assigned to incident places regardless of the fact whether the places are served by Station 2 (station affected by underpass construction) or not. After that, DID model was applied to the newly created dataset and the results (refer to Figure 4.6a & Figure 4.6b) indicated that the interaction between the time and treatment dummy were not significant, which is as expected. This implied that the treatment only affected the treated group and not control group.

Placebo Test

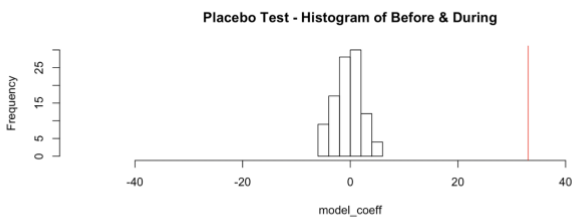


Figure 4.7a: Placebo - Before and During

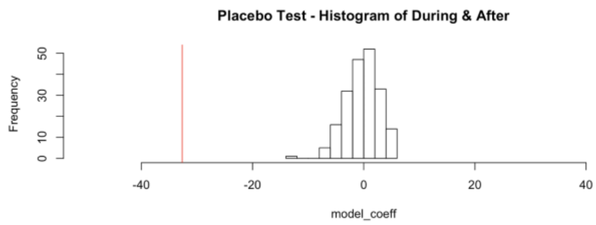


Figure 4.7b: Placebo - During and After

From DID model, it can be seen that the treated group corresponds strongly to the underpass construction. However, this cannot be firmly concluded that the response time changes is solely due to the construction of the underpass. Therefore, a placebo test was conducted to shuffle the treatment point, as well as control and treated groups.

From histograms on all the coefficients from the placebo test iterations (refer to Figure 4.7a & Figure 4.7b), it is clear that the means were close to zero. Compare with the actual model, there were no overlapping between the true coefficient and coefficients from the placebo tests. Hence, this test validated that the fire engine response changes were mainly due to the underpass construction.

Further Analysis (FA)

```
Call:
lm(formula = formula1, data = data_BD_network)

Residuals:
    Min      1Q  Median      3Q     Max 
-548.05  -86.50  -32.39   20.63 2541.43 

Coefficients:
                              Estimate Std. Error t value Pr(>|t|)    
(Intercept)                   5.174197  43.416342   0.119   0.9052    
time                         52.285732  20.454033   2.556   0.0107 *  
tr1                         -13.846118  18.664976  -0.742   0.4583    
closeness                   307.619551 147.983720   2.079   0.0378 *  
distance1                     0.089378   0.004911  18.200   <2e-16 ***
FHRESPONSECODENon Emergent  120.132869  11.619146  10.339   <2e-16 ***
time:tr1                    -19.085566  24.575517  -0.777   0.4375    
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Residual standard error: 198.2 on 1356 degrees of freedom
Multiple R-squared:  0.2411,	Adjusted R-squared:  0.2377 
F-statistic: 71.79 on 6 and 1356 DF,  p-value: < 2.2e-16
```

Figure 4.8a: FA - Before and During

```
Call:
lm(formula = formula1, data = data_AD_network)

Residuals:
    Min      1Q  Median      3Q     Max 
-417.96  -86.84  -38.04   22.06 2542.45 

Coefficients:
                                       Estimate Std. Error t value Pr(>|t|)    
(Intercept)                           87.580794  50.520864   1.734   0.0832 .  
time                                 -38.483538  19.924988  -1.931   0.0536 .  
tr1                                  -23.846568  23.869508  -0.999   0.3180    
closeness                            197.159465 179.040062   1.101   0.2710    
distance1                              0.087389   0.004955  17.636   <2e-16 ***
FHRESPONSECODEEmergent - Downgraded    2.359569  66.988324   0.035   0.9719    
FHRESPONSECODENon Emergent           125.766166  12.552351  10.019   <2e-16 ***
time:tr1                              17.992710  24.263509   0.742   0.4585    
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Residual standard error: 199.6 on 1340 degrees of freedom
Multiple R-squared:  0.2333,	Adjusted R-squared:  0.2293 
F-statistic: 58.26 on 7 and 1340 DF,  p-value: < 2.2e-16
```

Figure 4.8b: FA - During and After

Further analysis was done for the treatment group (fire station 2), to analyse if in-degree count of incident node matters in various stages of the underpass construction. When in-degree is more than 1, it means that multiple fire stations could respond to the incident node (other than fire station 2). The higher in-degree could be associated with easy accessibility from the various stations, this could also mean an overall lower response time at these locations. However, results (as shown in Figure 4.8a and Figure 4.8b) were not significant which suggest that the number of fire stations serving the incident locations did not impact response times.

6. Conclusion

Boulder Fire Rescue teams in respective fire stations have strived to meet the national standard of response with first fire engine within 6 minutes for 90 percent of the time, to make Boulder a safe place to live and work. To achieve that, firefighters not only need to be well-trained, well-equipped, but also must arrive in time, besides alarm handling and turn-out time.

From the Difference-in-Difference (DID) causality analysis, it showed that construction of Baseline road underpass project did cause a significant difference in the fire response time before, during and after the constructions. As such, it could be concluded that introducing new routes, be it for vehicles or pedestrians, could have a positive impact on response times due to improved connectivity and reduction in road congestion.

The future work could be carried out against fire response time on the possible network structure whereby fire incident sites shall be allocated as nodes, of which nodes had fire incidents happened at the same period of time (within 30 mins of each other) were being connected together (refer to Figure 6.1). The results from this analysis provide insights on locations that have fire around the same time to help allocate resources.

Appendix A

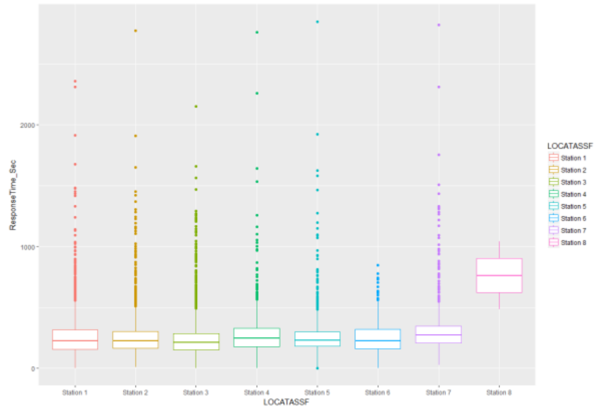


Figure 2.1a: Boxplot of response time by stations

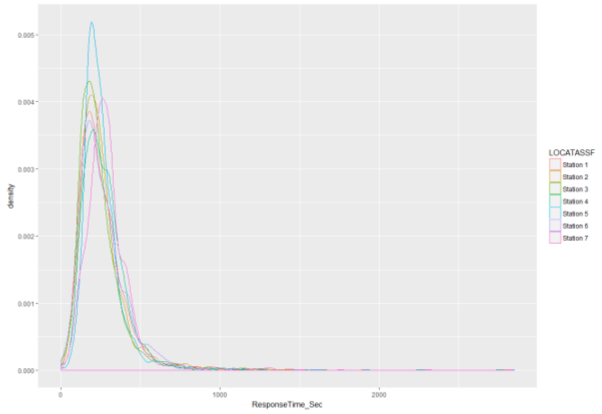


Figure 2.1b: Density distribution plot of response time by stations

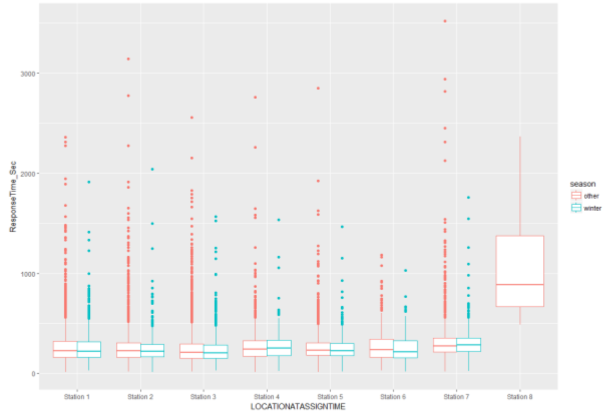


Figure 2.2a: Boxplot of response time winter vs others

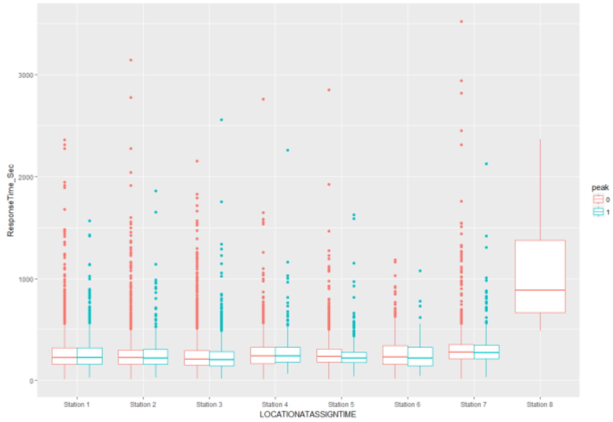


Figure 2.2b: Boxplot of response time peak vs non-peak

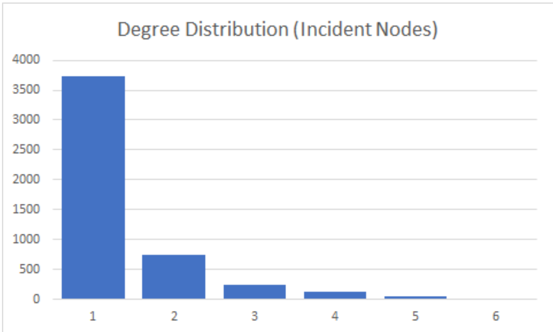


Figure 3.1: Nodes degree distribution

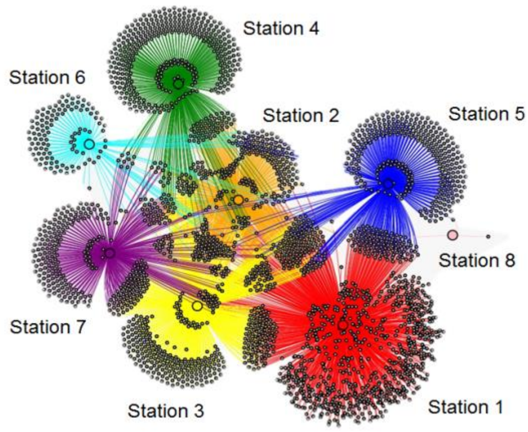
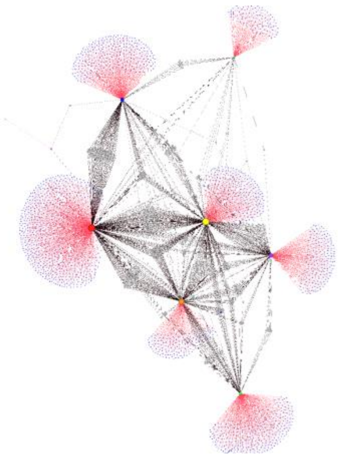


Figure 3.2: Network visualization: Edge coloured by stations



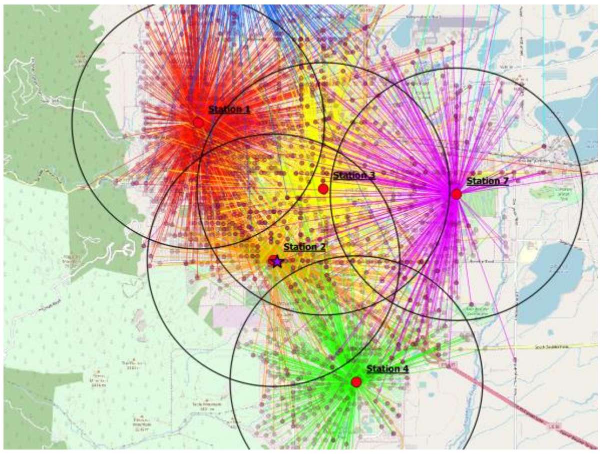


Figure 3.3: Network visualization: Edge coloured by number of in-degrees

Figure 4.1: Fire Stations Serving Space

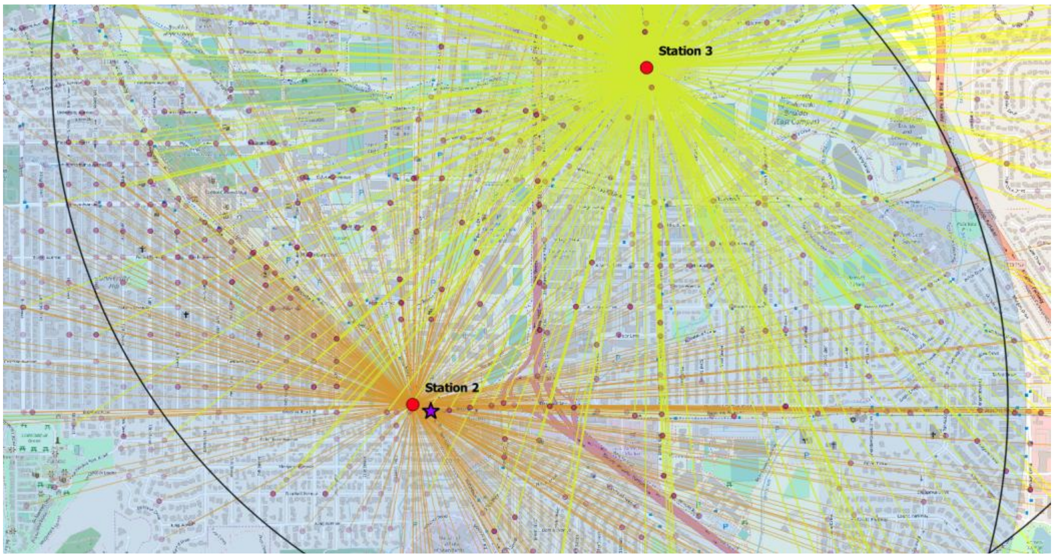
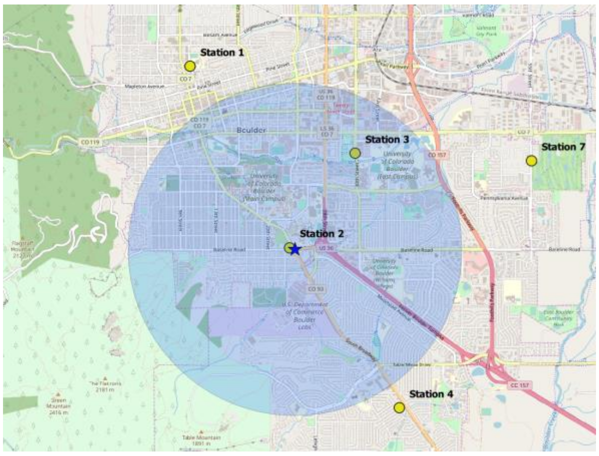


Figure 4.2: Station 2 and Station 3 responds area



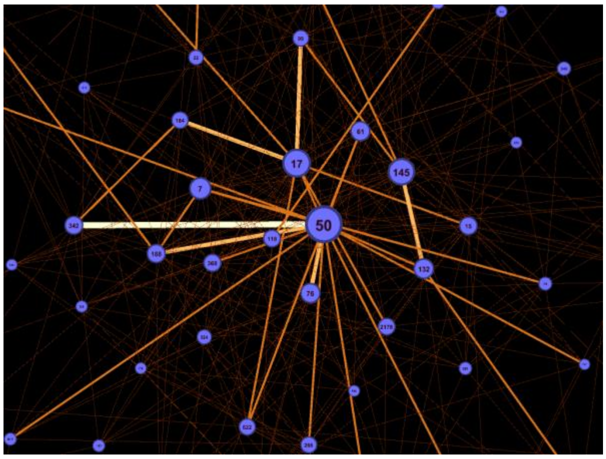


Figure 4.3: Assumed construction impact area

Figure 6.1: Future Work – Connection signify fire happening within same period