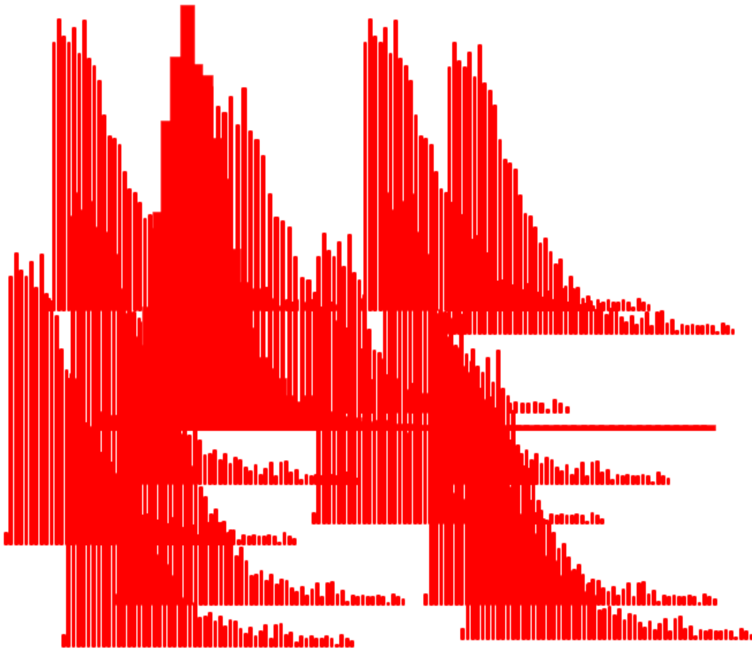
Developing a fire response test bench based on NFID



Adriano O. Solis, Ali Asgary, Jenaro Nosedal-Sánchez and Beatrice Zaccaro

March 1, 2018

UNIVERSITY OF THE FRASER VALLEY
CENTRE FOR PUBLIC SAFETY & CRIMINAL JUSTICE RESEARCH

YORK UNIVERSITÉ UNIVERSITY
School of Administrative Studies

Table of Contents

Executive Summary

Based on assumptions of completeness and consistency of fire incident data reported in the National Fire Information Database (NFID) for the 11-year period from 2005 through 2015, the research team had proposed to develop, by leveraging relevant information in the NFID, a simulation engine that would provide fire departments across Canada with a tool for fire prevention, risk analysis, preparedness, training, and response management.

Our initial evaluation of the various NFID data fields, however, showed very serious gaps both in terms of missing data values (blanks) as well as apparent inconsistencies in the data as reported. More importantly, our review of annual reports of at least four cities (three in Ontario and one in Alberta) showed that fire incidents constitute very small percentages of overall incidents they have reported responding to. This has rendered development of the simulation model using NFID data, as previously envisioned, unattainable.

We requested the assistance of the Vaughan Fire and Rescue Service (VFRS), whose officials agreed to provide relevant information in their 2009-2016 database, subject to a non-disclosure agreement between York University and the City of Vaughan. We were provided full 2009-2016 incident datasets (including responding units, civilian casualties, and firefighter casualties).

We proceeded to develop a modelling and simulation (M&S) framework involving two separate simulation models: (i) an *Incident Generation Engine*, a discrete event simulation model using colored Petri nets, which creates a list of incidents based on empirical distributions over time of emergency incidents and their key attributes, and (ii) a *Response Simulation Model*, an agent-based simulation model which uses as inputs the list of incidents generated by the first model. Both simulation models have been tested and preliminary results are reported here. While verification, validation and accreditation (VV&A) have constantly been conducted in the development and application of the two models, both models are may still be further refined and improved.[1]

[1] This is an updated version of our research project report on 'Developing a fire response simulation test bench based on NFID'. The proposal as submitted to the Canadian Association of Fire Chiefs in December 2016 had specified a 12-month project timetable. Delays in project approval/contracting resulted in access to the NFID datasets by research team members commencing only on April 12, 2017, even as project completion and report submission deadline remained specified as December 31, 2017. We submitted a preliminary draft on that date, while indicating submission of an updated report by March 1, 2018.

Project Objective

This research project was initiated to develop a simulation engine leveraging the National Fire Information Database (NFID) in order to provide fire departments across Canada with a data driven tool for evidence-based planning and response to fire incidents, thereby helping them create safer communities.

Financial support was provided in the form of a grant from the Canadian Association of Fire Chiefs (CAFC).

NFID: Initial Analysis and Quality Assessment

DATA AVAILABILITY AND CONSISTENCY

The NFID was made available to the research team initially on April 12, 2017 – in two main data files, one with information about incidents and the other containing information about victims (civilians and firefighters) for the 11 years from 2005 through 2015. The incident dataset included 128 fields (columns) with 467,929 reported incidents (rows), while the victim dataset included 30 fields (columns) with 15,326 reported cases (rows). In addition, an *NFID Data Dictionary* and an *NFID User Guide* were provided.

After initial analysis, we reported to the CAFC Research Grants Administrator on April 28, 2017 about a number of issues/concerns with the datasets. Among others, we had found the following:

- Multiple incidents with the same Incident ID (*INCDNTID*). In one very extreme case, for instance, 142 incidents reported for Saskatchewan had the exact same Incident ID.
- Clarification was required with respect to definitions of certain fields, including apparent inconsistencies in values for certain fields. For example, an entry of 8 in the Building Height (*HEIGHT*) field may be interpreted either in terms of a building with 8 storeys or as 'Not applicable (vehicle, outside area, etc.)'.

We were referred to Statistics Canada's Project Lead, Canadian Centre for Justice Statistics, Social, Health and Labour Statistics, who – in a conference call with the research team on May 4, 2017 – provided insights and clarification on some of the fields in question.

On July 14, 2017, updated versions of the incident and victim datasets were released, as well as slightly modified versions of the *NFID Data Dictionary* and the *NFID User Guide*. The 'new' incident dataset contains the same number of incidents, but has 136 fields (columns). Notably, the first field in this updated dataset is the Linking ID (*LINK_ID*) which sequentially numbers the incidents from 1 through 467,929.

The current incident dataset accordingly contains 136 fields, which correspond to specific attributes that should be recorded/reported for each incident, all defined/explained, along with the coding values (i.e., individual categories, counts, magnitudes, etc.) in the *NFID Data Dictionary* and the *NFID User Guide*.

However, our macro-analysis of both the original and updated versions of the incident and victim datasets, we detected a very significant amount of missing values (blanks) that would have constituted critical inputs for our modelling and simulation.

Our first finding was that the NFID does not contain information for all Canadian provinces. Data for only six provinces (other than the Canadian Armed Forces as a seventh jurisdiction) are reported. Moreover, the NFID does not report 11 years of incidents for all these seven jurisdictions:

- Only 2005-2014 data are available for Ontario; data for 2015 are missing.
- Data for Saskatchewan cover only the years 2012-2015; data for 2005-2011 are missing.

In terms of the temporal occurrence of incidents, the data spreadsheet contains the following fields: *YEAR*, *MONTH*, *DATE*, *DAY*, and *TIME*. In exploring data availability in the NFID with respect to these fields, we found the following:

- *YEAR*: available for 100 % of the listed incidents.
- *MONTH* and *DATE*: available for 95% of the listed incidents; no data reported for New Brunswick and for Canadian Armed Forces.
- *TIME*: available for only 44 % of the reported incidents; not available for the entire incidents record from Ontario.

The following fields pertain to the location of each fire incident: *INCIDLOC* (Incident Location), *CSD* (Census Subdivision Code), *CSD_NAME* (Census Subdivision Name), *CMACA (*Census Metropolitan Area/Census Agglomeration*), CMA_NAME* (Census Metropolitan/Agglomeration Area Name).

- *INCIDLOC*: available for 94.4 % of the listed incidents. However, responses are not provided in a standardized form, which impairs their use for a reliable spatial analysis.
- *CSD* and *CSD_NAME*: available for 85.4 % of the listed incidents. In the case of Saskatchewan only 0.2 % of the listed incidents report the *CSD*.
- *CMACA* and *CMA_NAME*: available for only 70.4 % of the reported incidents.

A very relevant data field for purposes of modelling and simulation of fire department operational performance are the times to respond to incidents. In the NFID, the response time in minutes (*RESPONSE*), referring to the time between receipt of the alarm/call by the Fire department to the arrival of the first responders (i.e., Response Time of First Vehicle at the scene of the incident), is one of the fields. Unfortunately, this information is quite scarce in the NFID.

- *RESPONSE*: available only for the jurisdiction of Alberta (13.2% of the reported incidents).

In fact, a more detailed review of the *RESPONSE* data for Alberta indicates many inconsistencies in the coding. 31.4 % of the values are higher than 60 minutes (due to the count of such values, those cannot really be considered as potential statistical outliers). Moreover, 30.5% of all the reported values are “999”, which is clearly problematic. After removing the apparently wrongly coded values, the data goes down to only 68.1% of recorded responses, which translates into 9% of the overall incidents reported in the NFID.

Other relevant fields have to do with resources dedicated to the response, among others: *CREWSIZE*, *NUMBER OF ENGINES*, *NUMBER OF AERIALS*, *NUMBER OF TANKERS*.

- *CREWSIZE*: available for 50.4 % of the reported incidents, but, in fact, is only reported for Ontario. Of the responses recorded, 45.2 % are coded as “0” (which bears no meaning), and the remaining values range from 1 to 251 - which all clearly suggest the necessity of a verification of many of the reported values.

- *NUMBER OF ENGINES*: entries available for less than 1% of the listed incidents.

- *NUMBER OF AERIALS*: entries available for less than 1% of the listed incidents.

- *NUMBER OF TANKERS*: entries available for less than 1% of the listed incidents.

Since the locations of the incidents are not reported in a consistently useful way, an alternative relevant piece of information for our research project is the reported distance from the first responder location to the incident location. This information is provided by the *DISTANCE* (Distance from fire department to emergency, which is specified in kilometers) field.

- *DISTANCE*: available for 50.4 % of the listed incidents, and in fact only reported for the incidents from Ontario. However, 45.1% of the values entered are “0”, which may be interpreted as an actual distance shorter than 0.5 km or may represent improper coding for an undetermined/non-recorded distance. On the other hand, the remaining values are in the interval [1, 4600], with larger values being doubtful as actual distances in kilometers.

While the NFID represents a set of relevant data for the analysis of various factors associated with the occurrence of fires, a report issued in September 2017 by the the Canadian Centre for Justice Statistics [4], prepared for the Canadian Association of Fire Chiefs, summarizes the jurisdiction (provinces) that provided incident data for various NFID fields – in effect indicating other data gaps beyond the ones we have reported above.

FIRES IN RELATION TO OTHER EMERGENCIES

The proportion of fires and fire related incidents in relation to other types of emergencies that fire departments respond to, as the research team found, is perhaps equally as significant as, if not even more critical than, the issues and concerns raised above regarding availability and consistency/quality of the NFID data for purposes of our research. The relevance and usefulness of NFID as a national database – one that allows the development of evidence-based research to enable better understanding and awareness of fire incidents and create knowledge for improving fire department responsiveness – becomes doubtful when considering the fact that fire department operations cover way more than responding to fire incidents. We initially reviewed Toronto Fire Services operations data as released in July 2017:

https://www1.toronto.ca/wps/portal/contentonly?vgnextoid=e04015093da69510VgnVCM10000071d60f89RCRD.

In Figures 1-8, we report on breakdowns of emergency incidents that were responded to by the fire departments/services of four cities – Calgary, Ottawa, Toronto, and Vaughan – in each of the years 2011 and 2016. This is somehow indicative of evolution, in the case of these four cities, of incident breakdowns over the most recent five-year period (2011-2016). Fire departments' workloads clearly do not come exclusively, nor even principally, from fire or fire related incidents, as may be readily gleaned from these figures.

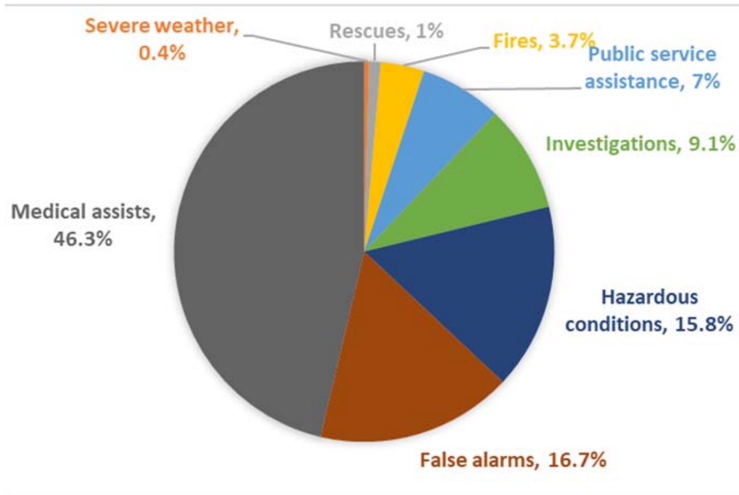


FIGURE 1. CALGARY FIRE DEPARTMENT: BREAKDOWN OF EMERGENCY INCIDENTS, 2011
(Data Source: Calgary Fire Department Annual Report 2011 [2])

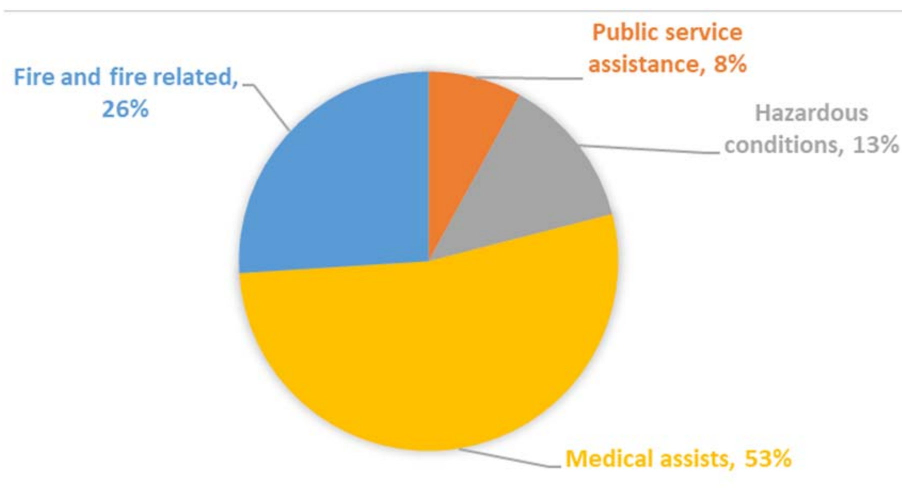


FIGURE 2. CALGARY FIRE DEPARTMENT: BREAKDOWN OF EMERGENCY INCIDENTS, 2016
(Data Source: Calgary Fire Department Annual Report 2016 [3])

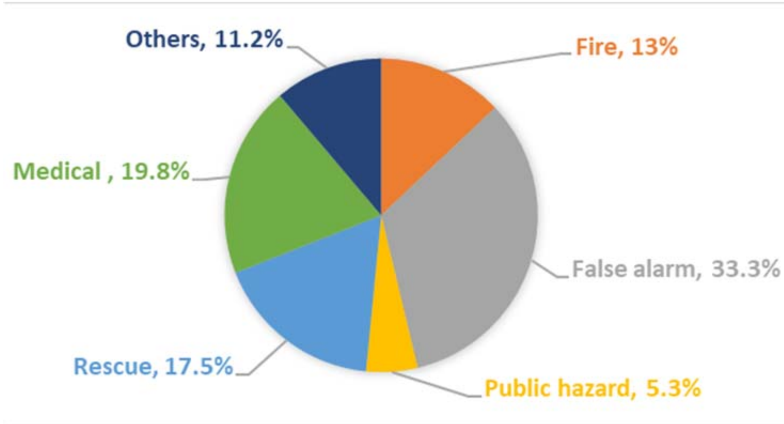


FIGURE 3. OTTAWA FIRE SERVICES: BREAKDOWN OF EMERGENCY INCIDENTS, 2011
(Data Source: Ottawa Fire Service 2011 Annual Report [7])

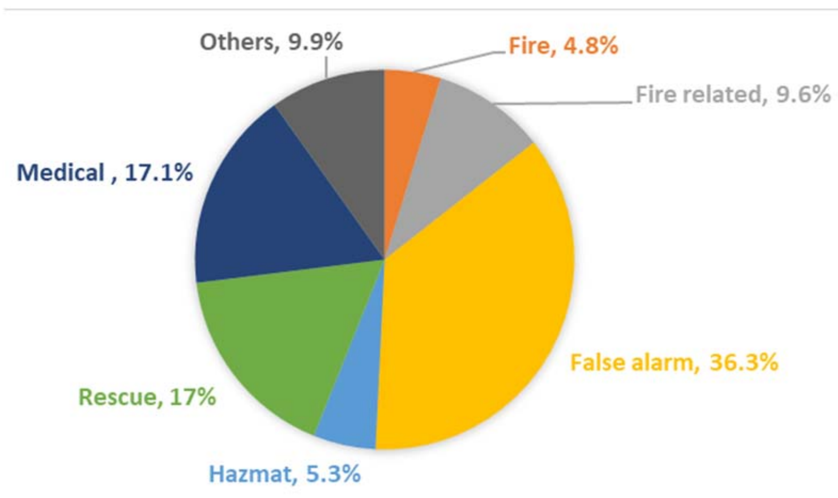


FIGURE 4. OTTAWA FIRE SERVICES: BREAKDOWN OF EMERGENCY INCIDENTS, 2016
(Data Source: Ottawa Fire Services 2016 Annual Report [8])

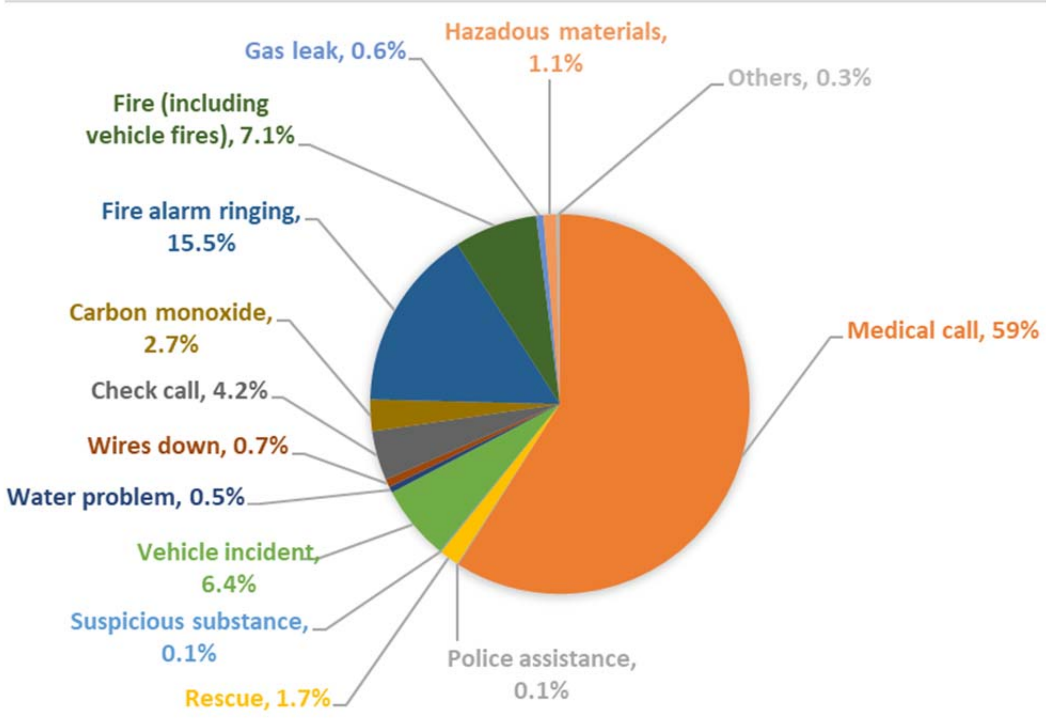


FIGURE 5. TORONTO FIRE SERVICES: BREAKDOWN OF EMERGENCY INCIDENTS, 2011
(Data Source: Toronto Fire Services 2011 Annual Report [9])

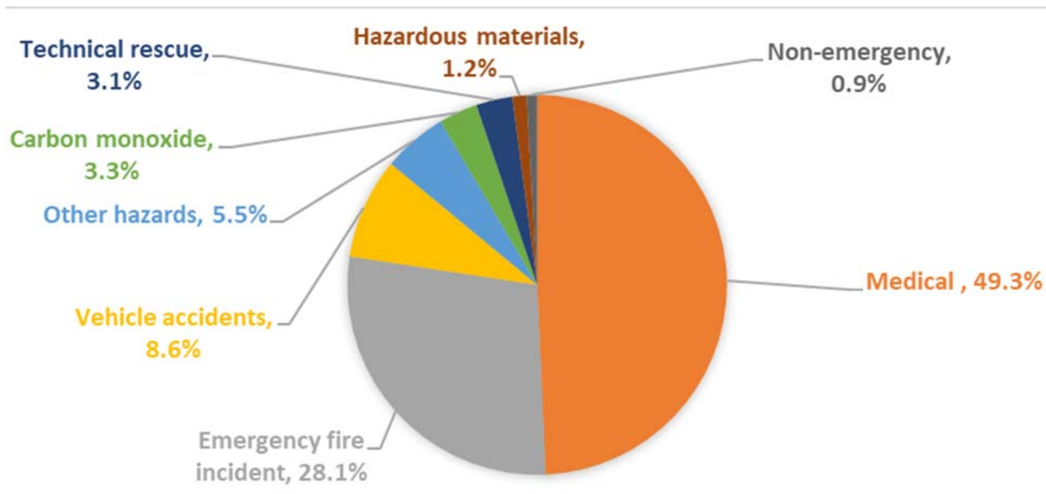


FIGURE 6. TORONTO FIRE SERVICES: BREAKDOWN OF EMERGENCY INCIDENTS, 2016
(Data Source: Toronto Fire Services 2016 Annual Report [10])

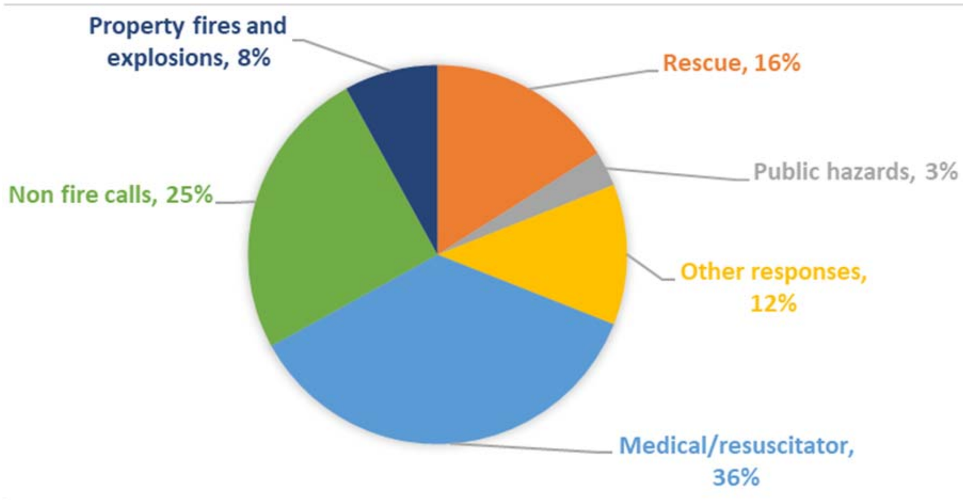


FIGURE 7. VAUGHAN FIRE AND RESCUE SERVICE: BREAKDOWN OF EMERGENCY INCIDENTS, 2011
(Data Source: Vaughan Fire & Rescue Service 2011 Annual Report [11])

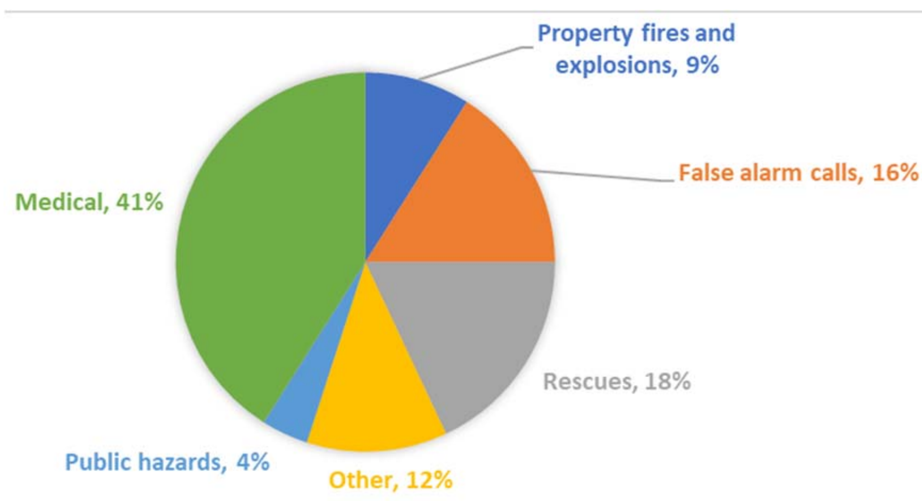


FIGURE 8. VAUGHAN FIRE AND RESCUE SERVICE: BREAKDOWN OF EMERGENCY INCIDENTS, 2016
(Data Source: Vaughan Fire & Rescue Service 2016 Annual Report [12])

In 2011, for instance, for these four cities, the percentages of fire and fire related incidents to total incidents responded to by their fire departments ranged between 3.7% and 13% (see Table 1). Accordingly, these fire departments responded to much larger proportions of non-fire incidents – which would not be reported in the NFID. More significantly, the last two columns of Table 1 – corresponding to the numbers of fire incidents reported in the NFID fields *CMA_NAME* and *CSD_NAME*, respectively – indicate that very small proportions of fire department resource assignments actually found their way into the NFID in 2011. This observation would also apply to all other years in the 2005-2015 time horizon currently covered by the NFID.

				No. of Incidents Reported in NFID	
City	Total Incidents	Fire & Fire Related Incidents	% of Total	in Field *CMA_NAME*	in Field *CSD_NAME*
Calgary	50,520	1,869	3.7%	1,320	1,190
Ottawa	26,370	3,421	13.0%	1,164	1,126
Toronto	145,334	10,248	7.1%	6,925	3,368
Vaughan	10,166	813	8.0%	None	369

TABLE 1. FIRE INCIDENTS REPORTED IN NFID IN 2011 COMPARED WITH TOTAL INCIDENTS RESPONDED TO BY FOUR CITY FIRE DEPARTMENTS

It should be mentioned that, in some annual reports, the breakdown of incidents does not separate actual structural fires from other fire related emergencies (e.g., vehicle fires or open fires). Where differentiation of structural fires is made, a narrower range of 3% to 10% (Fraser Institute Research Bulletin, 2015 [6]). In terms of allocation of resources (fire vehicles and crews assigned), responding to fire incidents demands more resources than other incident types. For instance, in 2016, responses to fire incidents in Toronto corresponded to almost 60% of the unit responses (Toronto Fire Services 2016 Annual Report [10]). It is clear, nonetheless, that resources demanded by the other, more frequent types of emergencies have a direct impact on a fire department's ability to respond to fire incidents. For purposes of modelling and simulation of a fire department's operations, therefore, it is necessary to include all the categories of incidents responded to by a fire department.

In light of the above-cited gaps in key operational data (incident location, time of alarm receipt, response time, etc.), as currently reported in the NFID, our research team decided to seek the assistance of the Vaughan Fire and Rescue Service (VFRS), in the province of Ontario, in order to be able to develop a simulation model as envisioned in our proposal.

Our aim was to develop a fairly generic model that could be replicated for fire departments across Canada, for as long as the appropriate set of operational data are collected and maintained by such other fire departments. Our case study and the resulting simulation model would not have been possible without the assistance and active participation of key officials of VFRS (Fire Chief, Deputy Fire Chief, and a Fire Captain overseeing the maintenance of their incident database). The VFRS dataset consisted of operational data covering the years 2009 through 2016. Throughout the conduct of our case study and the associated modelling and simulation (M&S) effort, the VFRS officials provided clarification and guidance with respect to the interpretation and use of the relevant data fields.

The remaining sections of this report will describe the overall case study, including the information that we processed and the platforms/methods we employed to build the M&S framework. We decided to develop the simulation framework taking into account the standard information available in the case of VFRS at fire department level (in accordance with directives issued by the Office of the Fire Marshal of Ontario). Our research proposal had anticipated a sufficiently adequate level of detail and data availability in the NFID to allow for a meaningful and productive M&S of incident occurrence and fire department response.

Incident Dataset: Current Case Study

In this section, we describe the dataset made available by VFRS ('VFRS dataset' or 'VFRS data') for purposes of our case study and M&S effort. Consistent with the non-disclosure agreement, charts and tables present data provided with the consent of VFRS representatives.

The VFRS data cover eight years of consecutive incident records from January 2009 through December 2016. In order to address file size issues, the VFRS dataset was broken down and made available to the research team in several MS Excel worksheets:

a. Incident Main Features,

b. Incident Responding Units,

c. Incident Civilian Casualties,

d. Incident Firefighter Casualties, and

e. Incident Other Tables.

It is possible to extract from the VFRS data a set of key features related with incidents and response characteristics. Some fields coincide with those reported in the NFID on the incident information fields, such as *INCIDENT ID, ALARM TIME, RESPONSE TIME* and *INCIDENT LOCATION*. Some relevant fields in addition to those in NFID are: *TYPE OF INCIDENT* and *ON SCENE TIME*.

We initially undertook an assessment of data availability and quality. We sought to eliminate wrongly coded values and outliers. Of the above mentioned key data fields, the worst case, for *ON SCENE TIME*, provided 88% of utilizable data (available records after the cleaning up process).

In Figure 9, we present the percentage distribution of the incident records on an annual basis throughout 2009 to 2016. Monthly percentage distribution throughout 2009 to 2016 is presented in Figure 10.

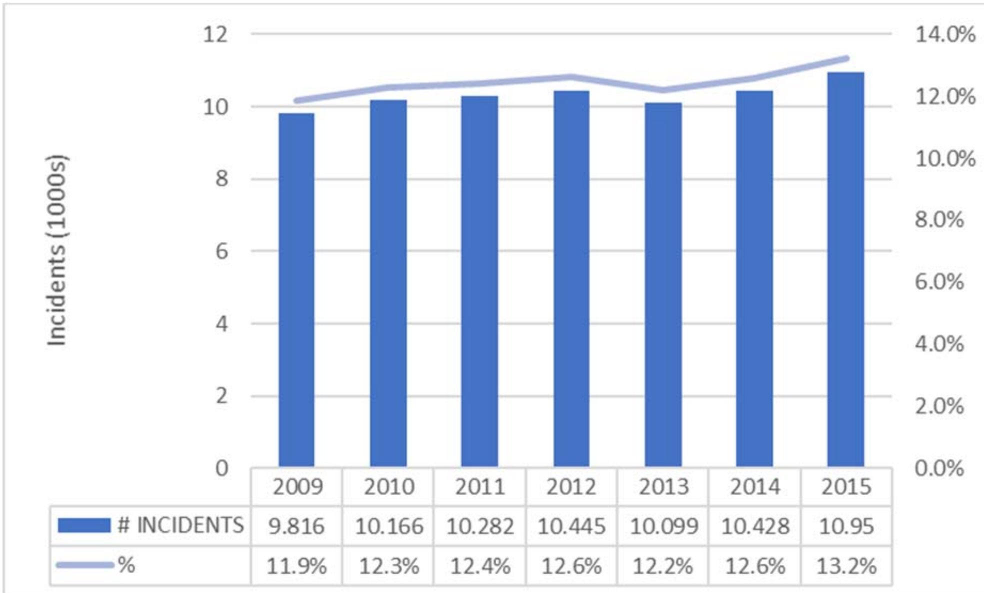


FIGURE 9. VFRS YEARLY INCIDENTS: NUMBER AND PERCENTAGE TO EIGHT-YEAR TOTAL (2009-2016)

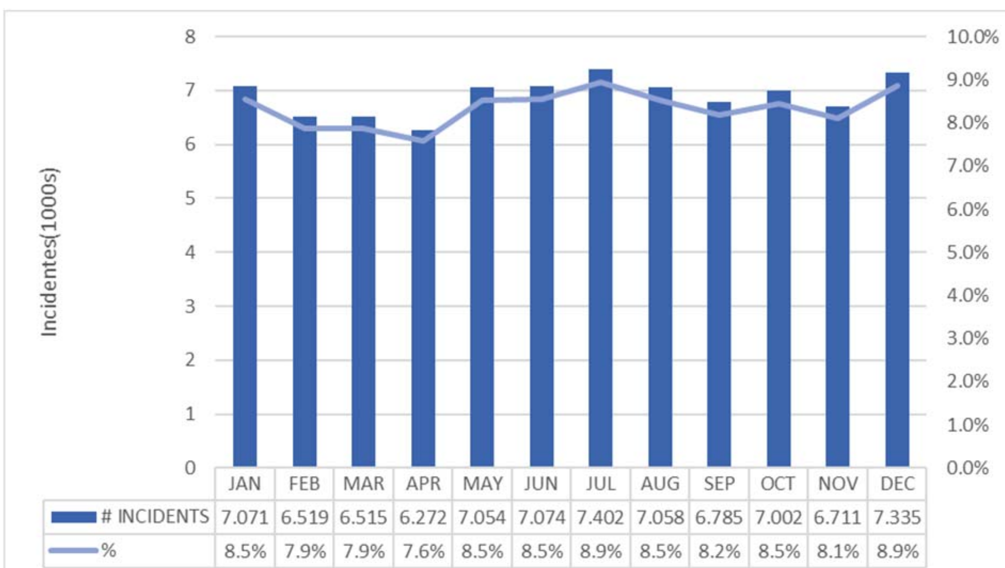


FIGURE 10. VFRS MONTHLY INCIDENTS: NUMBER AND PERCENTAGE TO EIGHT-YEAR TOTAL (2009-2016)

By observing the monthly numbers of incidents over 2009 to 2016 in Figure 11, it is possible to detect a slight upward (growth) trend.

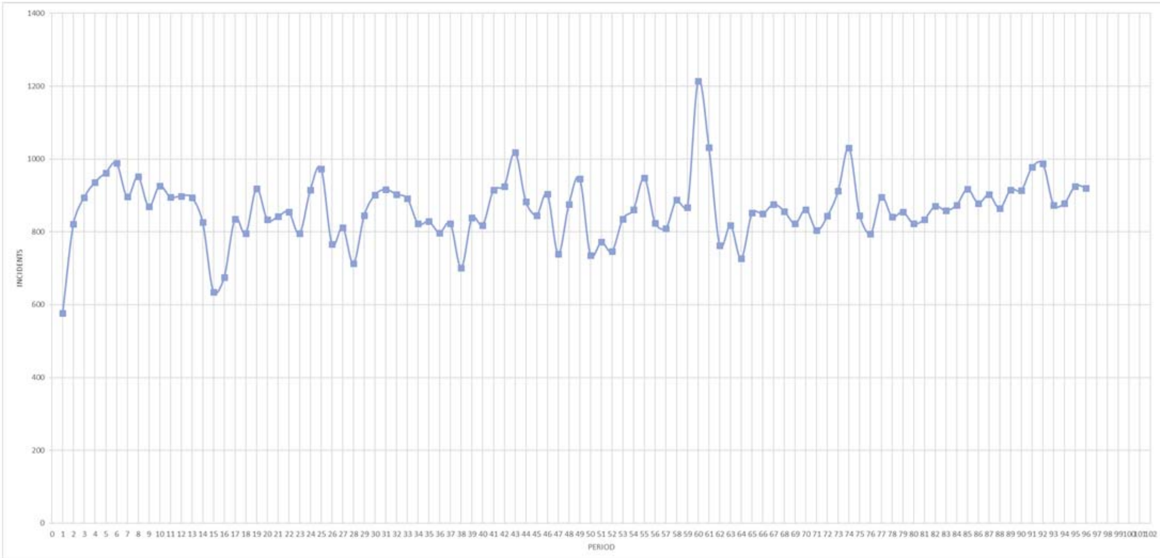


FIGURE 11. VFRS DATA: TOTAL NUMBER OF INCIDENTS PER MONTH (2009 TO 2016)

In Figure 12, we perceive an overall upward trend in the monthly number of vehicle rescues, with potential seasonal components (for instance, highs or lows during certain months). For fire incident calls, the plots in Figure 13 depicts a slight downward (decreasing) trend over the time. This downward trend in fire incidents may be indicative of successful fire prevention efforts by VFRS.

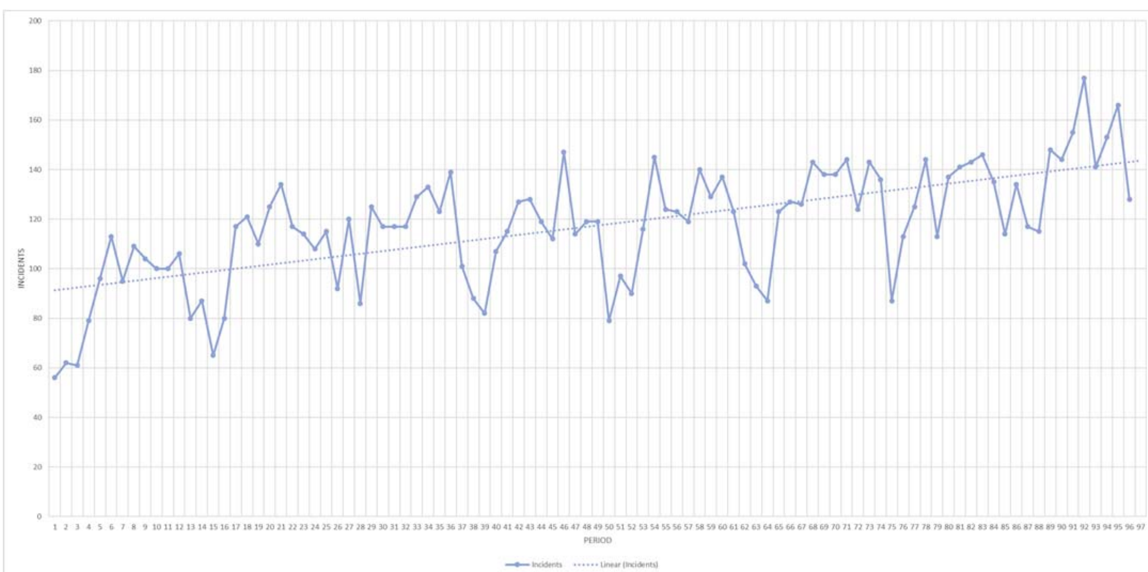


FIGURE 12. VFRS DATA: TOTAL VEHICLE RESCUES PER MONTH (2009 TO 2016)

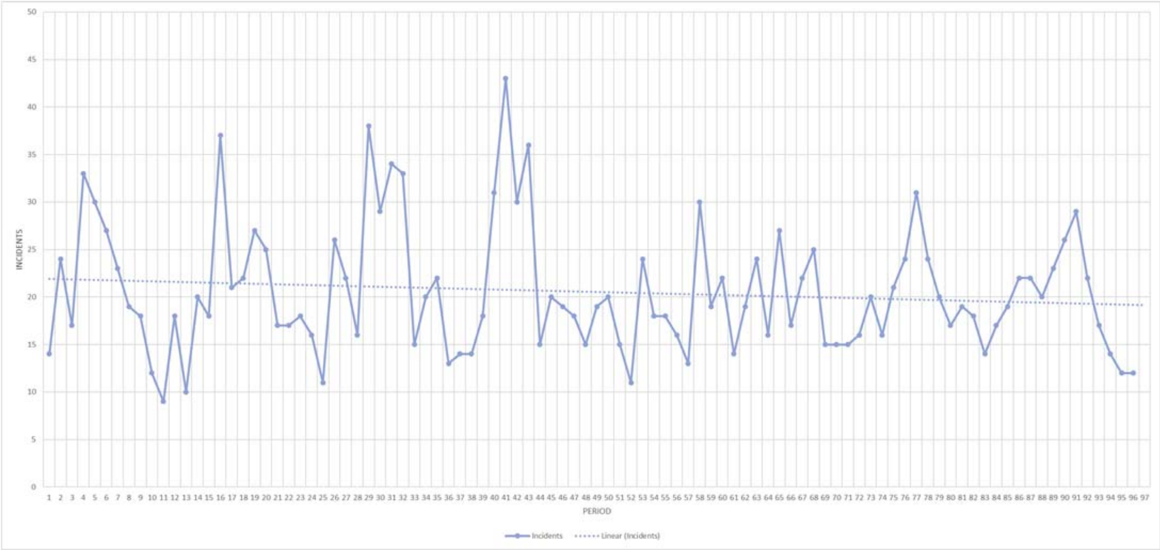


FIGURE 13. VFRS DATA: TOTAL FIRE INCIDENTS PER MONTH (2009 TO 2016)

From our analysis of time intervals (in minutes) between consecutive values of *ALARM TIME* (or "inter-arrival times"), we obtain the inter-arrival time distribution for emergency calls in Figure 14, the frequency histogram for the overall incident list represents the expected inter-arrival distribution, which suggests a negative exponential function and which is consistent with a Poisson distribution of "arrivals" of emergency calls. (The Poisson distribution commonly characterizes the arrival of customers in a service queuing system.)

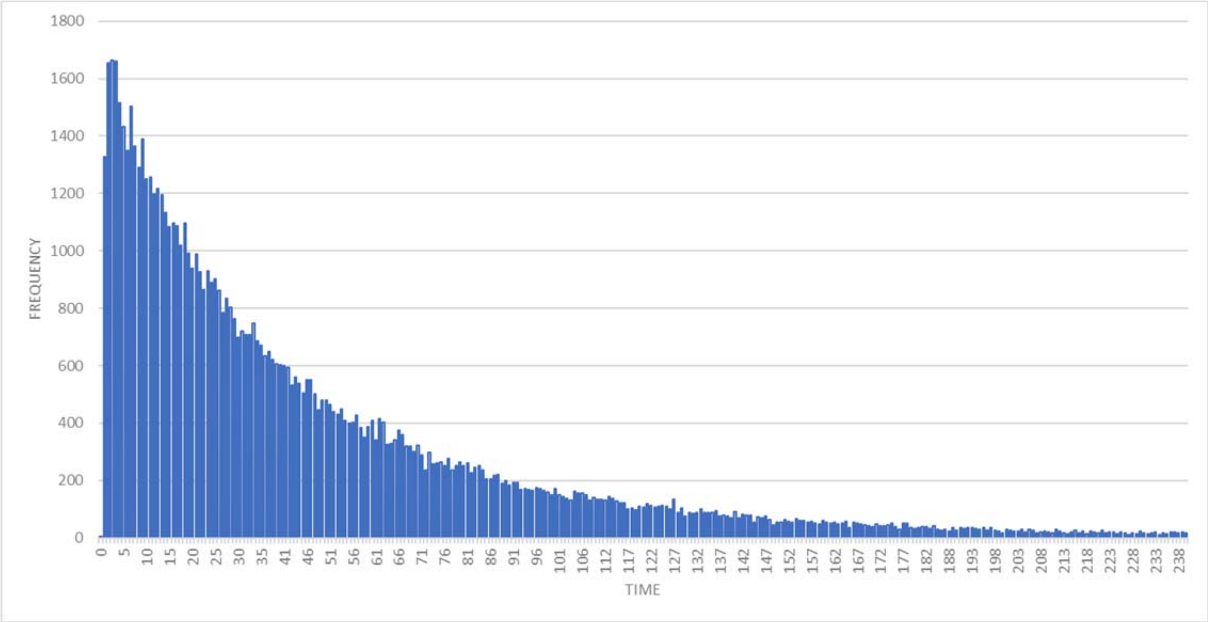


FIGURE 14. VFRS DATA: DISTRIBUTION OF TIME BETWEEN SUCCESSIVE CALLS, IN MINUTES

Figure 15 shows the distribution of *RESPONSE TIME* in the VFRS dataset. Based on usual experience in service systems, a 'mound shaped' – or normal – distribution is generally expected, which implies that the process is mature and well implemented (i.e., the process and organisation have passed the learning curve effect).

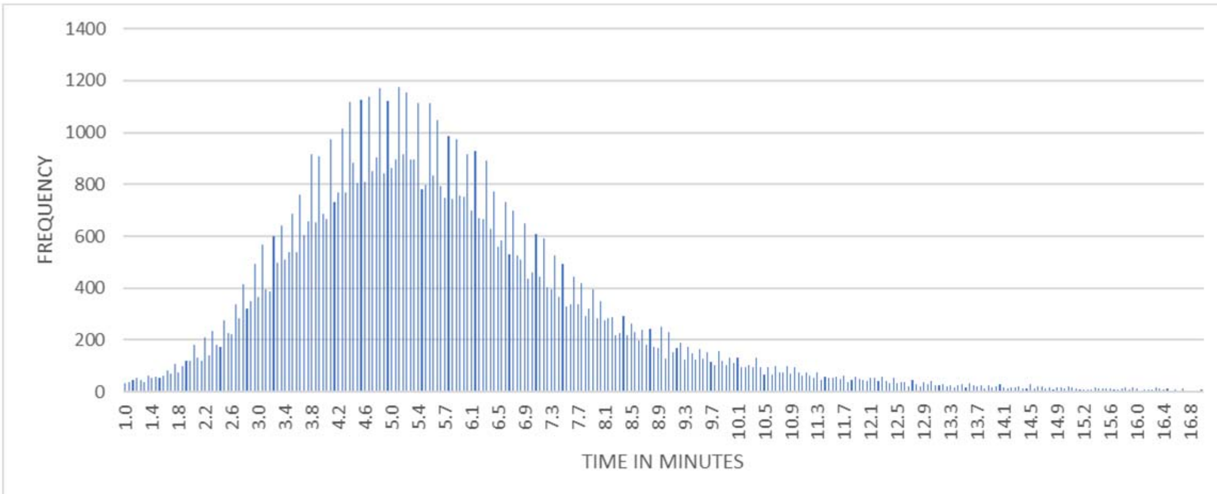


FIGURE 15. VFRS DATA: RESPONSE TIME DISTRIBUTION (ALL INCIDENT TYPES)

However, we apply in our simulation studies the actual empirical distributions of *RESPONSE TIME* according to various incident types. We analysed the *RESPONSE TIME* observed for each type of incident, obtaining different values of means and variability statistics.

A similar analysis is required for *ON SCENE TIME*. Figure 16 shows the overall distribution of *ON SCENE TIME*, although we found particular distributions (different shapes and parameters) across various incident types.

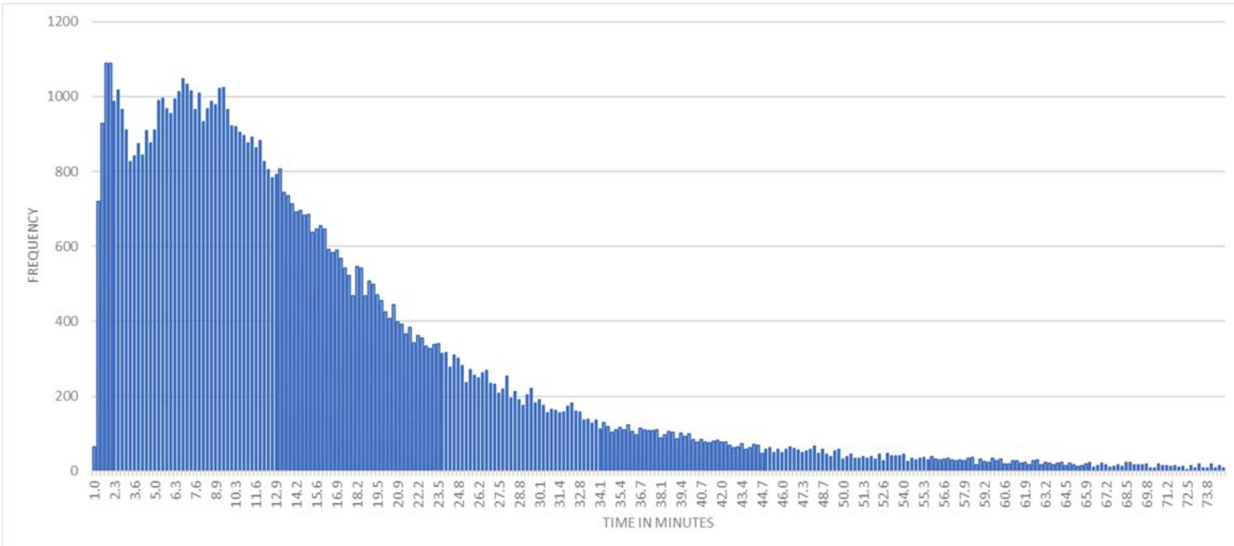


FIGURE 16. VFRS DATA: ON SCENE TIME DISTRIBUTION (ALL INCIDENT TYPES)

Besides the distributions of inter-arrival times, response times, and on scene times, another highly relevant component for M&S of emergency calls is their spatial distribution. The Longitude and Latitude coordinates recorded for each reported incident allow us to capture spatial patterns behind various incident types. We created a partition of the entire geographical region covered by VFRS, using a lattice granularity of 500 meters × 500 meters (0.25 km^2). 'Heat maps', as depicted in Figure 17, show the spatial analysis for:

a) All incident types in 2009;

b) All incident types in 2009-2016; and

c) Vehicle collision incidents in 2009-2016.

The values appearing in each cell are the numbers of accumulated incidents which have occurred in that area over the period specified. Each incident type produces a different spatial distribution pattern (i.e., 'hotspots' located in specific areas depending on the incident type), which is relevant for our M&S framework.

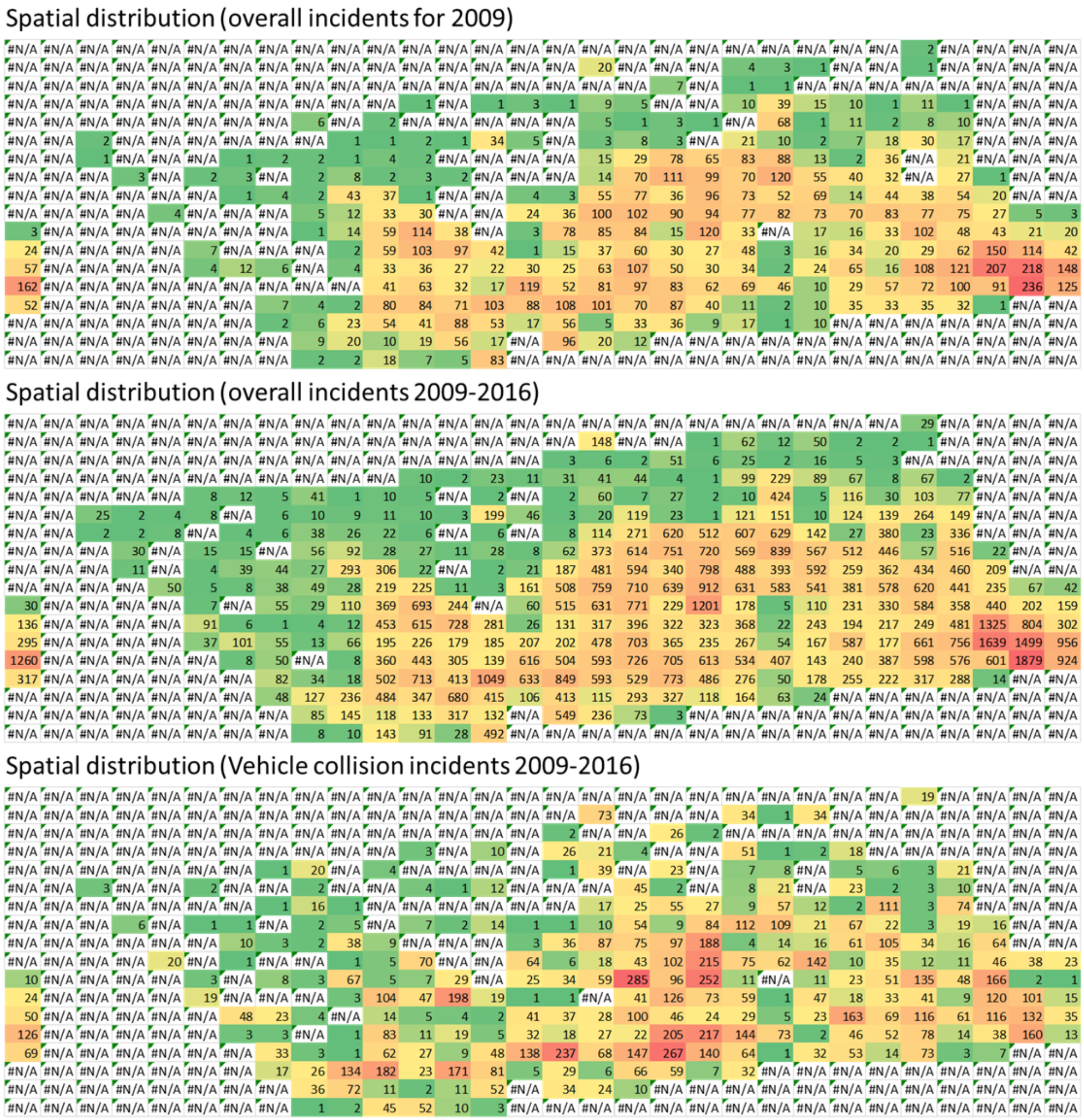


FIGURE 17. VFRS DATA: SPATIAL DISTRIBUTION ANALYSIS FOR SPECIFIC INCIDENT TYPES (2009-2016)

In addition to the spatial distribution patterns resulting from the longitude and latitude information for each incident, it is possible to estimate the expected travel distance from the responding station to the incident.

We are also able to obtain, for each reported incident, an *Alarm Processing Plus TurnOut Time (APPTOT)*, which is calculated as Roll-out Time stamp (when the vehicle rolls out of its home station) minus Alarm Receipt Time stamp (when the alarm is received at the VFRS communications centre). The distribution of *APPTOT* is presented in Figure 18. We must point out that the VFRS dataset only includes as data fields the Alarm Receipt Time stamp (*alm_time* in the Incident Main

Features file, or *notif_time* in the Incident Responding Units file) and the Roll-out Time stamp (*roll_time* in the Incident Responding Units file). We use the Roll-out Time stamp of the first responding unit at the scene in calculating the APPTOT. Since the originating station is not clearly identified by way of a separate data field, we assume that the first responding unit originates from the station responsible for the given Emergency Point. Alarm Processing Time and Turnout Time are not separately recorded.

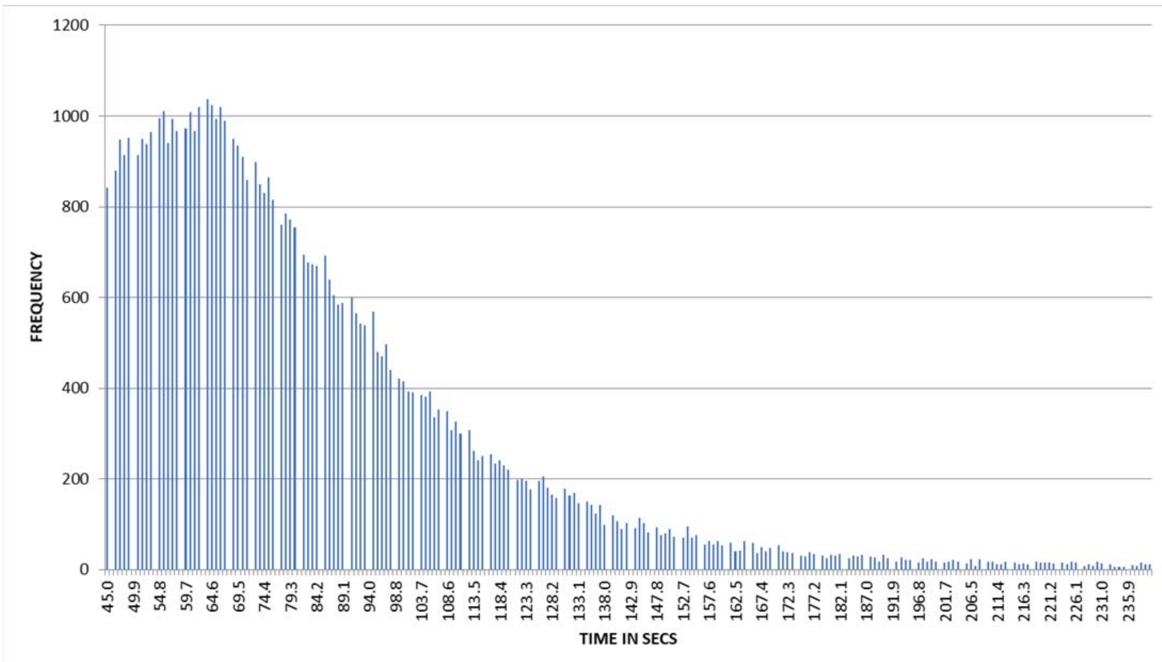


FIGURE 18. VFRS DATA: APPTOT DISTRIBUTION (ALL INCIDENT TYPES)

Our M&S framework involved two different simulation models running on separate platforms:

1. An *Incident Generation Engine*, developed and implemented using CPNTools 4.0 [5], which simulates the 'arrival' of incidents. Each incident occurrence is characterized by:

    a. type of incident,

    b. location,

    c. 'arrival' time (based on the time stamp of Alarm Receipt at the VFRS communications centre),

    d. APPTOT , and

    e. on scene time.

2. A *Response Simulation Model*, developed and implemented using AnyLogic 8.0.5 [1].

These two separate simulation models are fully described in the two immediately succeeding two sections of this report.

Incident Generation Engine

In this section, we describe the first of two simulation models. This *Incident Generation Engine* produces a list of incidents (including the main features: type, location, 'arrival' time), which is generated based on the empirical distributions obtained for the key incident features. This incident list provides the inputs for the *Response Simulation Model*.

A conceptual overview of the integration of the information produced from the analysis of the VFRS dataset is presented in Figure 19.

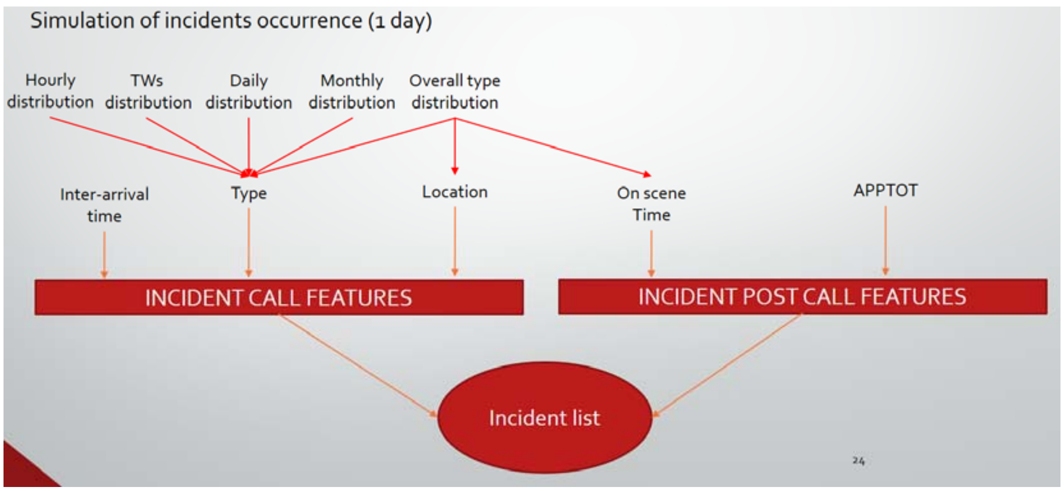


FIGURE 19. INTEGRATION OF EMPIRICAL DATA FOR SIMULATION OF THE INCIDENT LIST

The simulation of incident occurrences has been developed and implemented as a discrete event simulation model with CPNTools 4.0 [5] as the platform. The model takes simultaneously information from the empirical distributions, considering central tendency and variability statistics, of various data fields within the dataset to generate:

1. type of incident, considering the probabilities of occurrence of specific types of incidents over time (at the level of frequencies on an hourly basis during the day), and at four different time windows (TWs) during the day (i.e. 0:01-5:59 h, 6:00-11:59 h, 12:00-17:59 h and 18:00-23:29 h.),

2. incident location, based on the 500 m × 500 m cells in the lattice as previously described,

3. incident 'arrival' time, based on the distribution of inter-arrival times between successive alarms,

4. APPTOT for the first responding crew depending upon the type of incident, and
5. on scene time for the first responding crew, depending upon the type of incident.

The generation of incidents for one day has been implemented using colored Petri nets with CPNTools 4.0 [5] as platform. An overview of the main components of the model (places, transitions, and arcs) is presented in Figure 20.

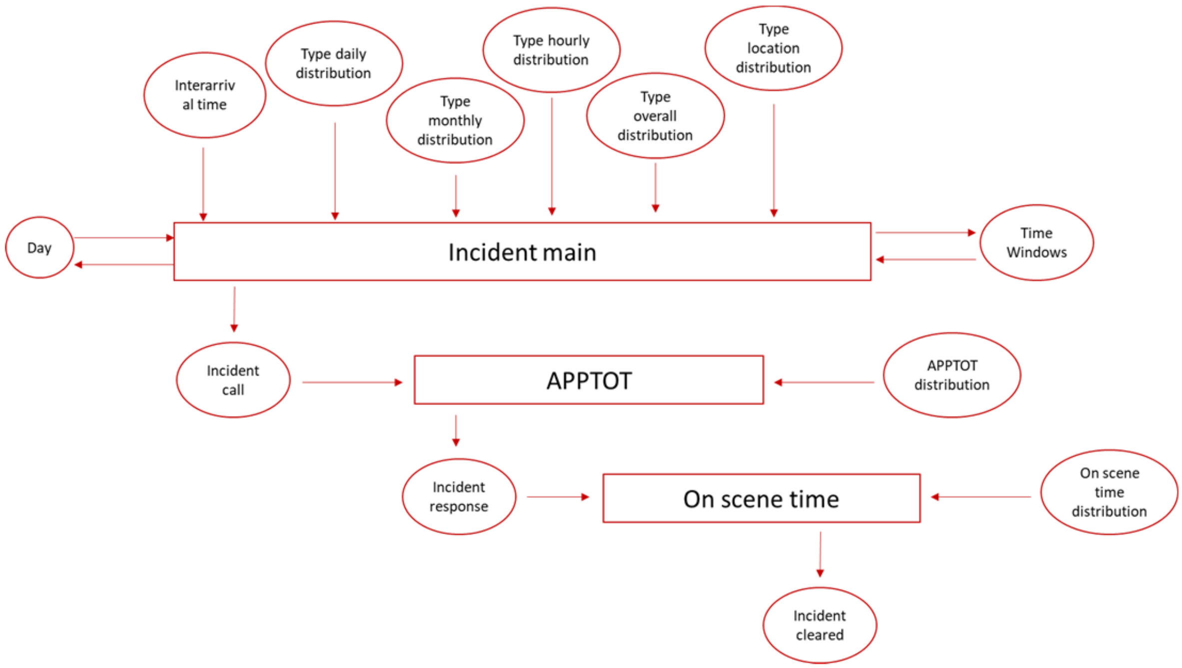


FIGURE 20. INCIDENT GENERATION ENGINE: MAIN COMPONENTS

The empirical distributions obtained from the VFRS dataset are the main inputs provided for the simulation that produces the incident list for an entire day. Descriptions of components (network nodes) are summarized in Table 2.

The output list includes the following features/attributes for each incident:

- ID: incident ID
- TP: incident type
- ST: spatial location (cell in the lattice)
- t1: inter-arrival time
- PT: APPTOT
- OT: on scene time

Name	Node type	Description
Incident main	Transition	Takes one value from each of the places (nodes) connected to simulate the main features for an incident (interarrival time, type, location).
APPTOT	Transition	Takes one value from the distribution depending on the incident type.
On scene time	Transition	Takes one value from the distribution depending of the incident type.
Day	Place	Contains the information of the day (Monday, Tuesday, etc.), Month (Jan, Feb, etc.) for the generation of the incident list.
Inter-arrival time	Place	Contains the inter-arrival time, obtained from the distribution of time between successive calls.
Type daily distribution	Place	Contains the incident occurrence distribution per day for each incident type.
Type monthly distribution	Place	Contains the incident occurrence distribution per month for each incident type.
Type hourly distribution	Place	Contains the incident occurrence distribution per hour for each incident type.
Type overall distribution	Place	Contains the incident occurrence distribution for each incident type.
Type location distribution	Place	Contains the incident occurrence distribution per location (cells of 0.5 km × 0.5 km) for each incident type.
Time windows	Place	Contains the incident occurrence distribution within the specified TWs for each incident type.
Incident call	Place	Contains the incidents generated along with the main features (interarrival time, type, location)
APPTOT distribution	Place	Contains the estimated APPTOT, obtained from the distribution for the overall incident types.
Incident response	Place	Contains the incidents generated along with the main features plus the preparation time.
On scene time distribution	Place	Contains the incident on scene time distribution for each incident type.
Incident cleared	Place	Final node with all the features simulated: interarrival time, type, location, APPTOT, on scene time.

TABLE 2. DESCRIPTIONS OF INCIDENT GENERATION ENGINE COMPONENTS (PLACES AND TRANSITIONS)

Response Simulation Model

The incident list created using the *Incident Generation Engine* serves as input into the second model – the *Response Simulation Model*. In order to recreate the environment in which VFRS responds to emergencies of various types occurring throughout the day, we developed and implemented an agent-based simulation model using the AnyLogic 8.0.5 simulation platform [1].

While the Incident Generation Engine is based on discrete event modelling, we used *Agent-Based Modelling* (ABM) to develop our Response Simulation Model. ABM is best described as a decentralized, individual-centric approach to modelling. In this approach, individual participants have their own behavior and are referred to as *agents*.

Within the AnyLogic simulation platform, we are able to transform reported longitude and latitude information on incidents (as well as fire stations) into usable Geographic Information System (GIS) coordinates which allow simulation of vehicular travel on city streets.

MODEL DESCRIPTION

The agents that come into play in the model are:

- Dispatcher – the person who receives the 911 call from the Emergency Point and decides to alert the appropriate Station to attend to the incident;
- Emergency Point – an entity that develops and changes its status based on the actions of the other agents;
- Station – the agent that receives the execution order from the Dispatcher and changes its status according to availability of resources; and
- Vehicle – the entity that receives the dispatching order from the available Station. It also uses the GIS Map in order to take the appropriate route. (Based on VFRS practice, a crew of four firefighters mans each responding vehicle.)

FIGURE 21. AGENTS USED IN THE MODEL

As far as the simulation model animation view is concerned, a scaled representation of the city's Fire Districts and stations involved helps the user to directly visualize what is happening in the environment in terms of entities and the flow of resources (see Figure 22).

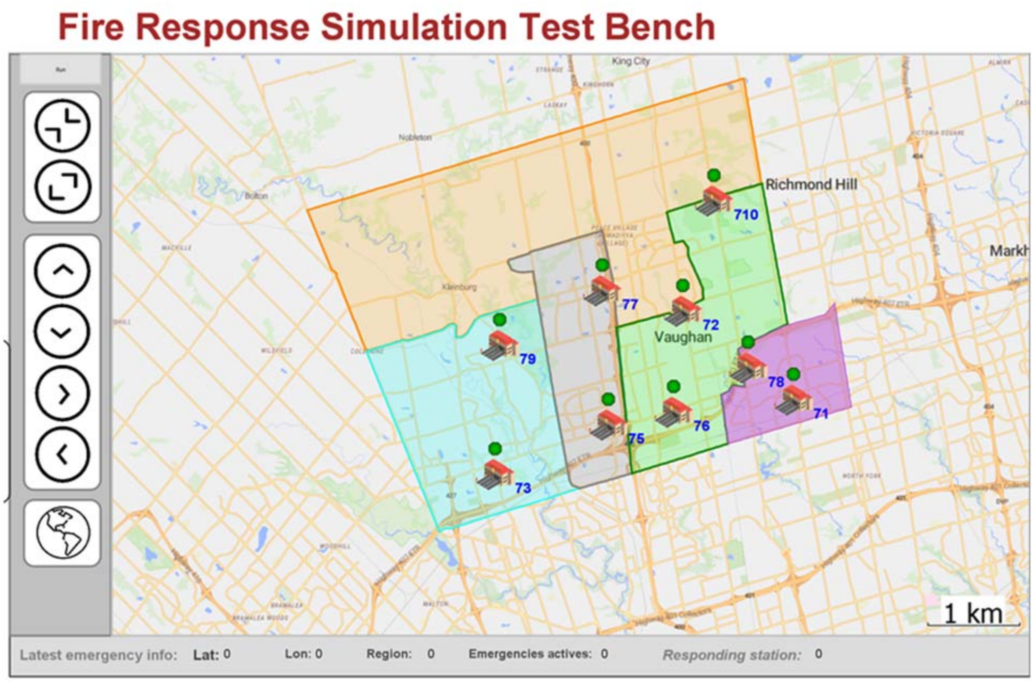


FIGURE 22. SUBDIVISION OF THE CITY OF VAUGHAN INTO FIRE DISTRICTS AND CURRENT FIRE STATION LOCATIONS

The GIS Map shape enables one to display and manage GIS (Geographic Information System) maps in the model. The GIS Region element to markup some closed area on the map was used, and it is possible to add a new region or modify the region shape. Each point of the region has latitude and longitude coordinates, defined in degrees. It is also possible to use a shapefile (.shp) as an input to build the region inside the City District. The definition of regions is very important because the logic inside the model is structured on different decision levels based on these boundaries. The agent that is charged to take these decisions is the Dispatcher that receives the latitude and longitude information from the incident. Using these values it is possible to determine which region (district) and station takes principal responsibility for the incident.

In the initial Response Simulation Model development and testing, our model was restricted to one responding vehicle per incident. According to current VFRS protocol, different types of incidents call for 1, 2, or 4 responding vehicles. In applying current protocol, we obtained the following distribution of number of responding units required:

Number of Trucks per Protocol	%-age
1	60.5%
2	34.1%
4	5.3%
	100.0%

Thus, only 5.3% of incidents would be expected to require four responding vehicles. We also looked into the actual numbers of responding units, as reported in the Incident Responding Units file (January 2009 – December 2016) and derived the following distribution:

Vehicles responding	# incidents	% occurrence
1	57,494	69.4%
2	16,819	20.3%
3	2,864	3.5%
4	1,712	2.1%
More than 4	3,909	4.7%
	82,798	100.0%

Based on actual numbers of units responding to emergency incidents in 2009-2016, 89.7% involved one or two responding vehicles while only 10.3% involved more than two vehicles.

Thus, whether based on current protocol or on experience, we see a relatively small percentage (5.3% and 10.3%, respectively) of incidents requiring more than two responding units. Our team decided that a Response Simulation Model involving either one or two responding units would enable a relatively simple working model, but one which still is roughly indicative of resource requirements. Accordingly, all incident type codes requiring either two or four responding vehicles per VFRS protocol are – in our Response Simulation Model, as currently developed – assigned two responding units.

Currently, the model uses the following logic to send resources where they are needed:

1. Consider the stations that are in the same region as the incident.
2. Choose the Nearest Station in Region by Route.
3. Check the availability of resources.
4. Check the resources needed by the Emergency Point.
5. If the available Station resources are exactly the number of needed resources of Emergency point, send all vehicles required.
6. If not, send the vehicles available in the Station and update the resources needed decreasing the value.

7. If resources needed to Emergency Point is greater than zero, check other Stations in Region and:

7.1 If the available Station resources are exactly the number of needed resources of Emergency point, send all vehicles required.

7.2 If not, send the vehicles available in the Station and update the resources needed decreasing the value.

8. If resources needed by Emergency Point is greater than zero, choose the Nearest Station by Route among all others in the entire city with available resources and:

    8.1 If the available Station resources are exactly the number of needed resources of Emergency Point, send all vehicles required.

    8.2 If not, send the vehicles available in the Station and update the resources needed decreasing the value.

It is also possible to change this decision-making scheme in connection and consistent with current operating procedures/protocols as used in a given city. In order to better understand the whole logic that is in the model, a pseudo-algorithm has been written below that can represent the main actions and the decision process step by step.

```
input file: EmergencyPoints (Identification Code, Latitude,  Longitude, Time stamp, APPTOT, On scene time, Emergency Code, number of vehicles needed)
read File per row
calculate in which Region the EmergencyPoint is
input file: Stations (Station ID, Latitude, Longitude, Region of belonging, Number of Vehicles)
read File per row
Set Station in GIS Map;
for (each EmergencyPoints.file.row){
 if  (the model time is equal to incident time)
   EmergencyPoint.status changes to Active;
   Emergency Point send the message: alarm;
   Dispatcher receives message;
   Dispatcher receives information: EmergencyPoint parameters;
 Select Stations in Region;
  Choose the Nearest Station in Region by Street Distance;
   if (Resources Available && resources needed>0)
     Dispatcher send the message: operation;
     Station receives message;
     Station.Status changes to Operation;
     Station send the message: go;
     Vehicle receives the message;
     Vehicle.status changes to Preparation;
     Station_selected.numberVehicles --;
    resources needed--;
     Vehicle goes to (EmergencyPoint.Latitude, EmergencyPoint.Longitude)
  else
      (Are there other Stations in Region?)
      if (Resources Available && resources needed>0)
         Dispatcher send the message: operation;
         Station receives message;
         Station.Status changes to Operation;
```

```
            Station send the message: go;
            Vehicle receives the message;
            Vehicle.status changes to Preparation;
            Station_selected.numberVehicles --;
            resources needed--;
            Vehicle goes to (EmergencyPoint.Latitude, EmergencyPoint.Longitude)
        else
            if ( resources needed>0)
              (identify available Stations.outsideRegion)
              Choose the Nearest Station by Street Distance;
              Dispatcher send the message: operation;
              Station receives message;
              Station.Status changes to Operation;
              Station send the message: go;
              Vehicle receives the message;
              Vehicle.status changes to Preparation;
              Station_selected.numberVehicles --;
              resources needed--;
              Vehicle goes to (EmergencyPoint.Latitude, EmergencyPoint.Longitude)
activate function Check.Station.Availability;
  if ( numberVehicles == 0 )
    Available = false;
    Station.Status changes to Unavailable;
Vehicle.status changes to OnRoute;
Agent.Vehicle arrival -> send the message: OnSite;
EmergencyPoint receives the message;
EmergencyPoint.status changes to Rescue;
Time=OnSceneTime;
EmergencyPoint.status changes to Cleared;
Vehicle.status changes to Returning;
Vehicle goes to (Station.Latitude, Station.Longitude)
Agent.Vehicle arrival -> Station_selected.numberVehicles ++;
activate function Check.Station.Availability;

}
```

With an agent-based model, we populate the environment with the various entities that interact with each other. As mentioned previously, the agents used are the incidents, the vehicles, the dispatcher, and the stations. The stations are placed in the map by uploading a file; hence, in this model, any actual number of stations may be specified. Each station's parameters will include the following information:

- Station ID;
- Latitude;
- Longitude;
- Region to which the station belongs; and
- Number of vehicles.

Regarding the number of vehicles per station, it is possible to set it at the beginning of the simulation through appropriate sliders or by entering the number directly in a box (see Figure 23).

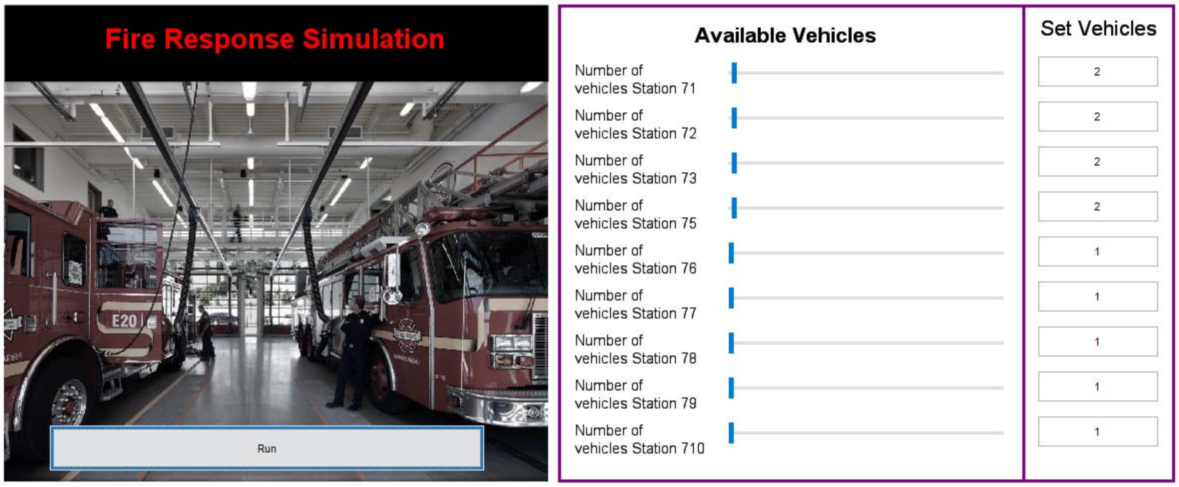


FIGURE 23. MODEL HOMEPAGE AND SETTING NUMBERS OF AVAILABLE VEHICLES

The operational capability of the stations depends on the availability of resources. The green symbol on top of a station means that the agent (station) is able to respond to an incident. When all the vehicles belonging to that station have been dispatched or they are already in preparation to attend to an incident, the station is unavailable in term of resources. For the purpose of showing the station unavailability, the black symbol on top of the station was designed, and it means that the agent is not able to respond to any incident. Figure 24 shows the symbol described previously in connection with station status. During this state of unavailability of the station, it is important to define the logic of implementation of the model and collect the output data appropriately.

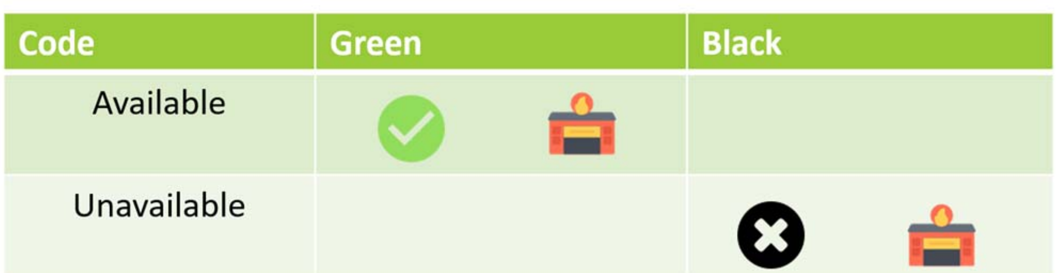


FIGURE 24. STATION STATUS AND RELATED SYMBOLS

For each station a certain number of vehicles is assigned. Each vehicle is an agent with its own characteristics and behaviors. To better understand how these types of agents behave in the model, the status of each vehicle has been summarized in the following list:

- *Waiting* is the status in which the vehicle waits at its station. This state means that the vehicle is available for assignment to an incident.
- *Preparation* status starts as soon as the alarm is received by the VFRS communications centre and lasts until the vehicle rolls out of the station. Since Alarm Processing Time and Turnout Time are not separately recorded, the model treats a vehicle as being in the 'Preparation' status throughout the period of time referred to as APPTOT, as provided by the Incident Generation Engine. (A station and a vehicle are assigned to an incident based upon the the longitude and latitude information of the Emergency Point.)
- The status *On Route* reflects the vehicle traveling towards the Emergency Point.
- The *On Scene* status reflects the vehicle being at the Emergency Point and attending to the incident.
- *Returning* is the status after the emergency has been cleared, with the vehicle traveling back to its home Station.

The vehicles reach the incident location using the existing roads and routes based on real spatial data. Furthermore, thanks to GIS Map features, the simulator chooses the fastest way to arrive at the incident. As already mentioned above, another extremely relevant entity within the model is the Emergency Point, with the following characteristics as specified by the Incident Generation Engine:

- Incident identification code;
- Latitude;
- Longitude;
- Alarm Receipt Time stamp (when the alarm is received at the VFRS communications centre);
- APPTOT;
- On scene time; and
- Incident type code.

The Emergency Point information is entered into the model as an input file, where each row represents an incident. The incident type code automatically determines the number of required vehicles to be assigned to respond to a given incident. Since the simulator allows the upload of the input file coming from the Incident Generation Engine, there are no restrictions on the number of emergencies that can be simulated in a run.

The Emergency Point agent is closely related to the other agents' status diagram, because it sends and receives information to/from all the other agents in the model. The different states related to an emergency point are listed below:

- *Inactive*: The state in which the incident has not happened yet;
- *Active*: The state in which the Emergency Point sent an alarm and it is waiting for a response;
- *Rescue*: State in which a responder has arrived at the Emergency Point;
- *Cleared*: The state in which the Emergency Point has been cleared.

By using statecharts one can visually capture a wide variety of discrete behaviors., For this reason, statecharts were used to better represent the various agent states in the model (as described above). Figure 25 includes the agents statecharts that were developed in the model to reflect the real environment process:

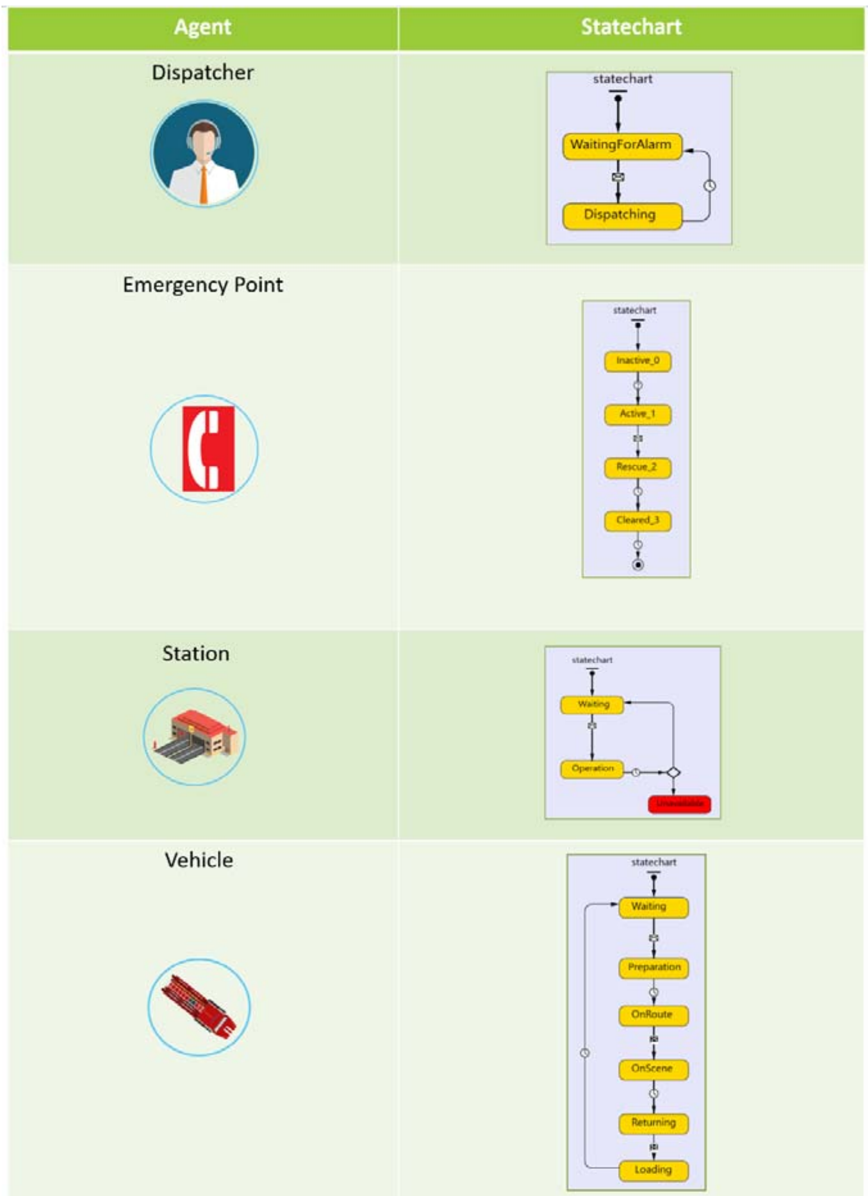


FIGURE 25. AGENTS' STATECHARTS

The simulation model, as developed, provides a set of indicators of operational performance. Such indicators are simply various performance measures related to the different rescues operations. To fulfill their purpose, such indicators are simple to understand. Once the simulation is completed, a button becomes available in the window, to allow the user to collect the simulation results available in terms of output files.

The output files contain the following performance indicators:

- Time period between alarm receipt and the end of the rescue procedures,
- Travel time of each vehicle used and the total time amount of all vehicles per day,
- Travel distances of each vehicles in terms of meters and the total amount of all vehicles per day,
- Accumulated number of the incidents over the time,
- Number of vehicles remaining per Station,
- Vehicles sent by other Stations for each Emergency point, when the Station that was supposed to rescue hasn't all vehicles needed available.

The simulation model homepage allows the user to choose between two options:

1. immediately launch the simulation run without worrying about model customization and agreeing with the default conditions and settings; or

2. modify pre-implemented default settings and customize the model input parameters, enabling the model to test different configurations.

The homepage contains different number of box where the user can setup the model parameters related to agent in the simulated environment, as shown previously (Figure 23). Each run includes the simulation of a day of activity of the fire department, during which various emergencies may occur according to the statistical outputs defined in the previous section. Figure 26 shows a view of the performance measures listed above that the simulation model is able to provide during the simulation and also collect in a dataset.

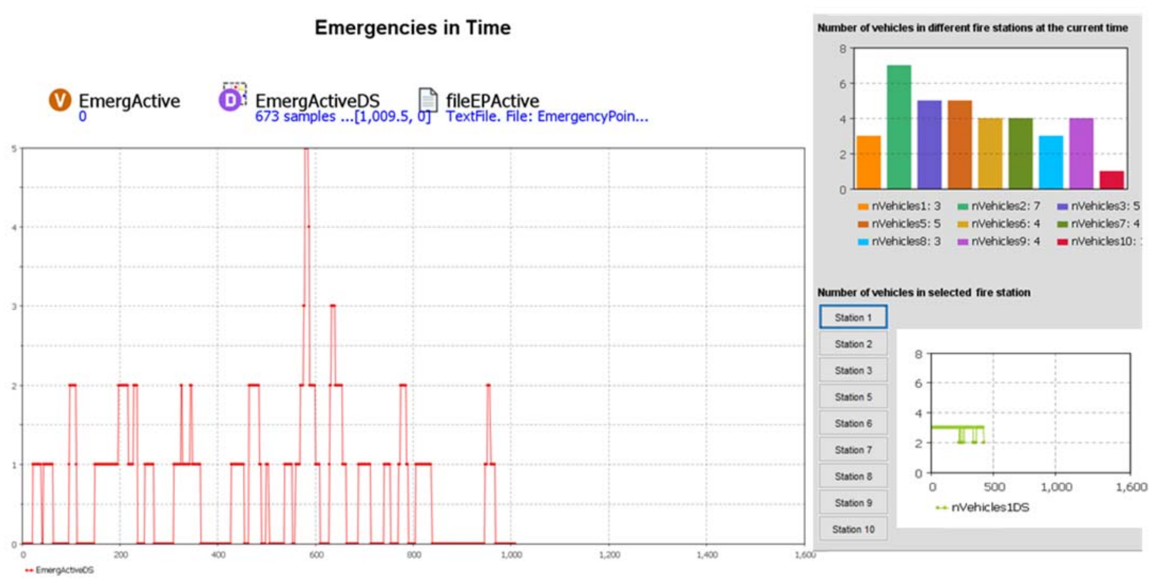


FIGURE 26. PERFORMANCE INDICATORS VISUALIZED DURING SIMULATION

SIMULATION RESULTS (FUNCTIONALITY VALIDATION OF THE MODEL)

Each replication of our simulation experiment simulates one day of VFRS responses to emergency incidents. We have thus completed and collected statistics from 180 replications (corresponding to a six-month period from January to June) of the experiment. In effect, 180 days of incidents were generated using the *Incident Generation Engine,* and the resulting incident list was used as input for the *Response Simulation Model*.

We present the distributions of response times on a monthly basis after eliminating outliers (nearly 5% percent of the simulated values). All the presented values were obtained by simulating the response times with empirical distributions derived from the Incident Generation Engine in combination with the Response Simulation Model. Figures 27-33 present the response time distributions obtained for each month from January to June.

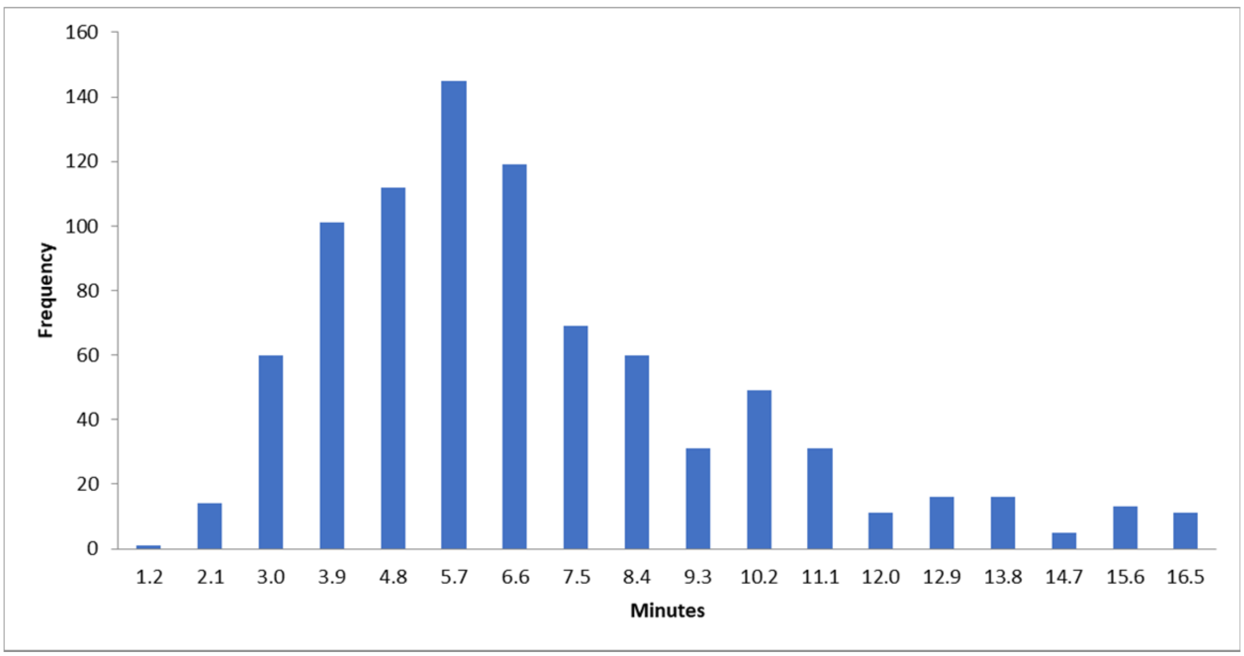


FIGURE 27. DISTRIBUTION OF SIMULATED RESPONSE TIMES, JANUARY

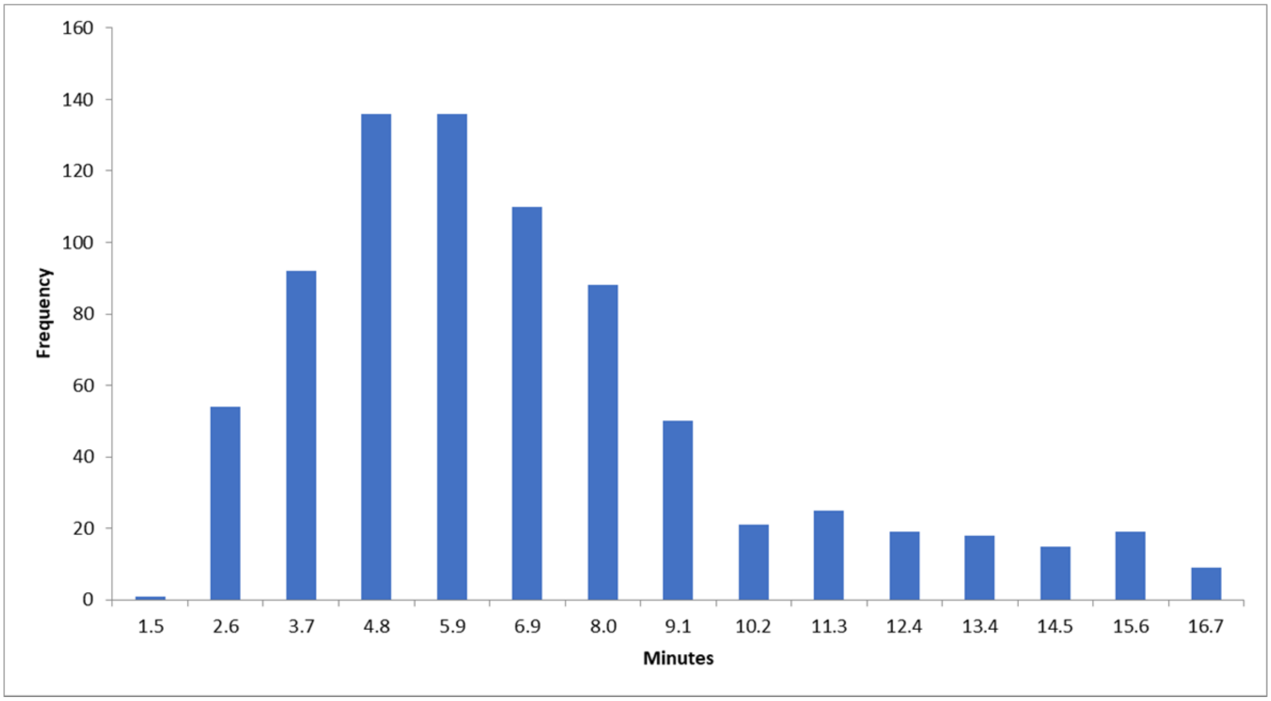


FIGURE 28. DISTRIBUTION OF SIMULATED RESPONSE TIMES, FEBRUARY

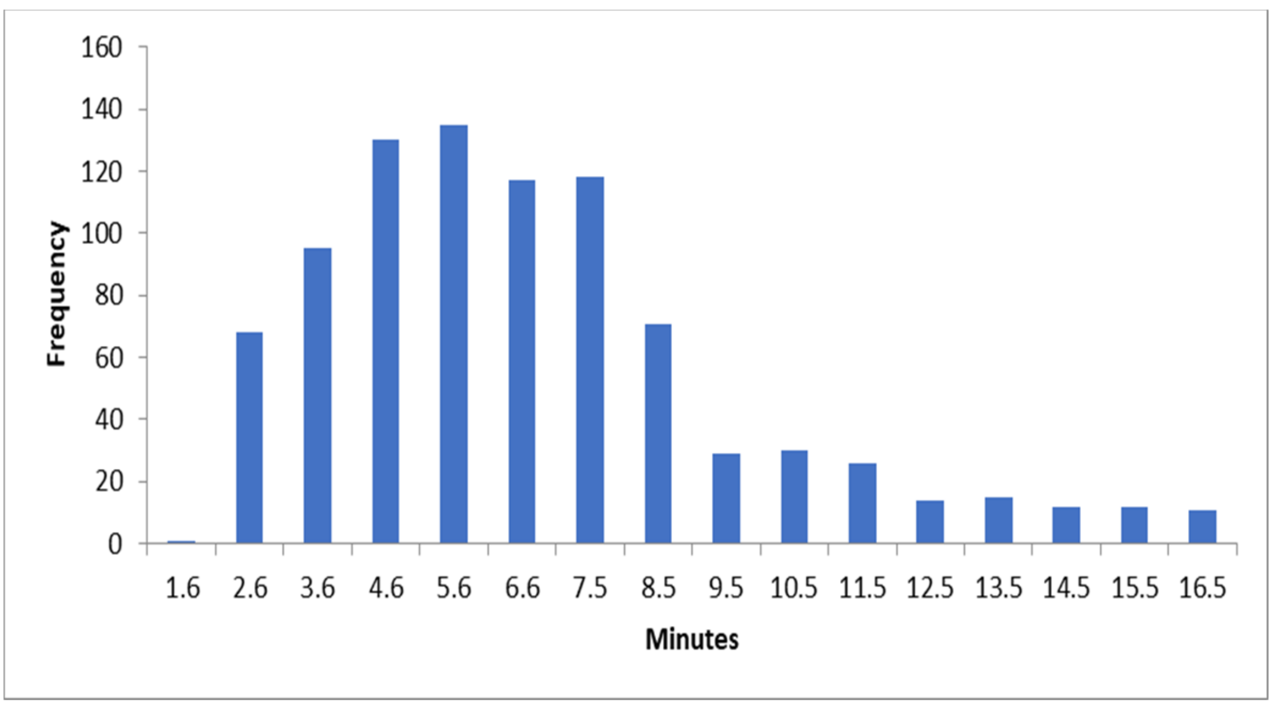


FIGURE 29. DISTRIBUTION OF SIMULATED RESPONSE TIMES, MARCH

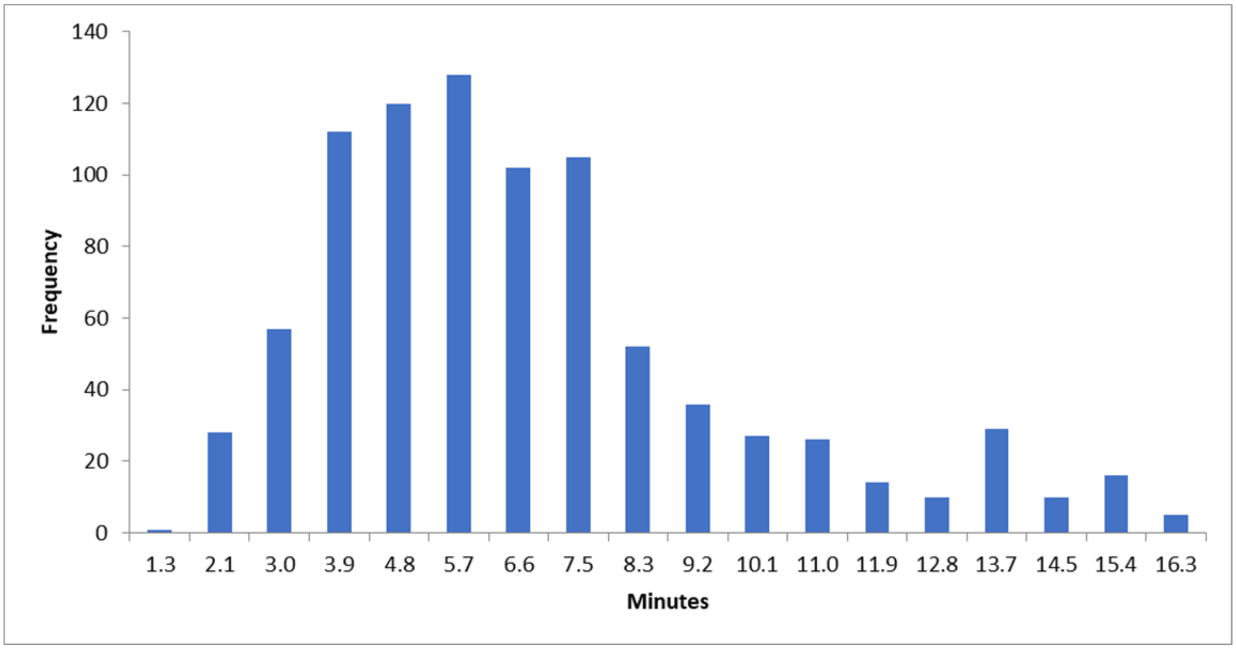


FIGURE 30. DISTRIBUTION OF SIMULATED RESPONSE TIMES, APRIL

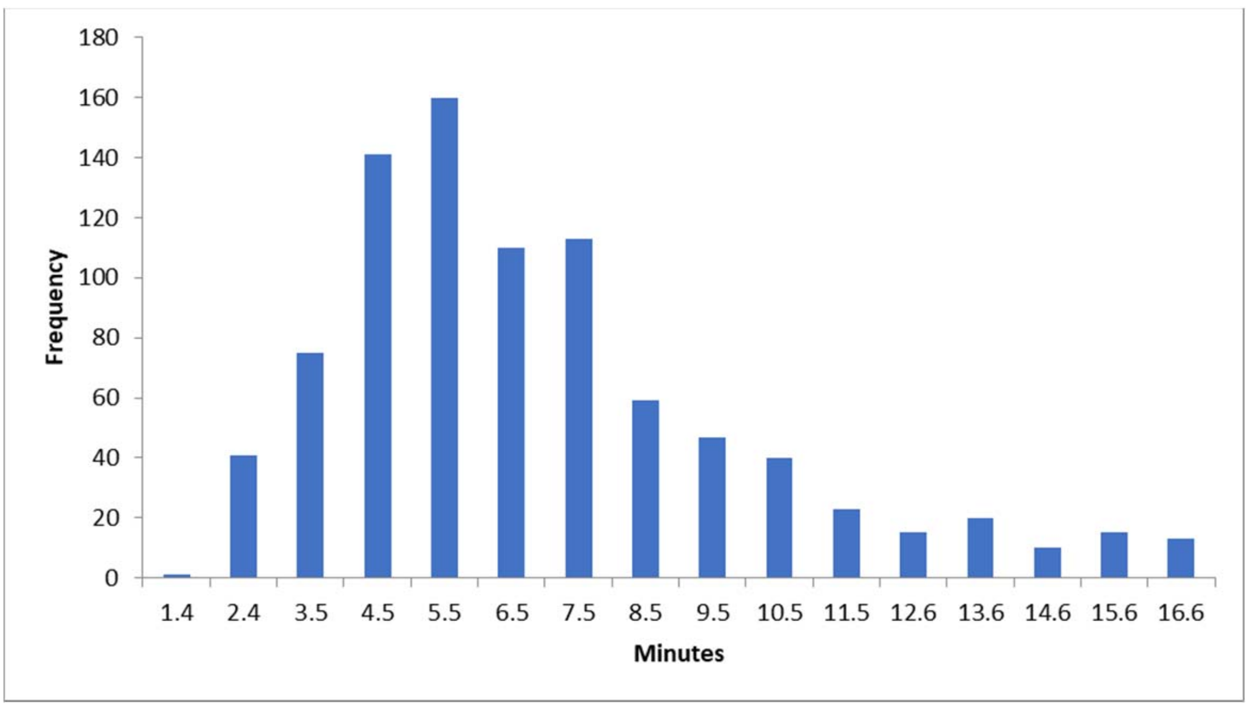


FIGURE 31. DISTRIBUTION OF SIMULATED RESPONSE TIMES, MAY

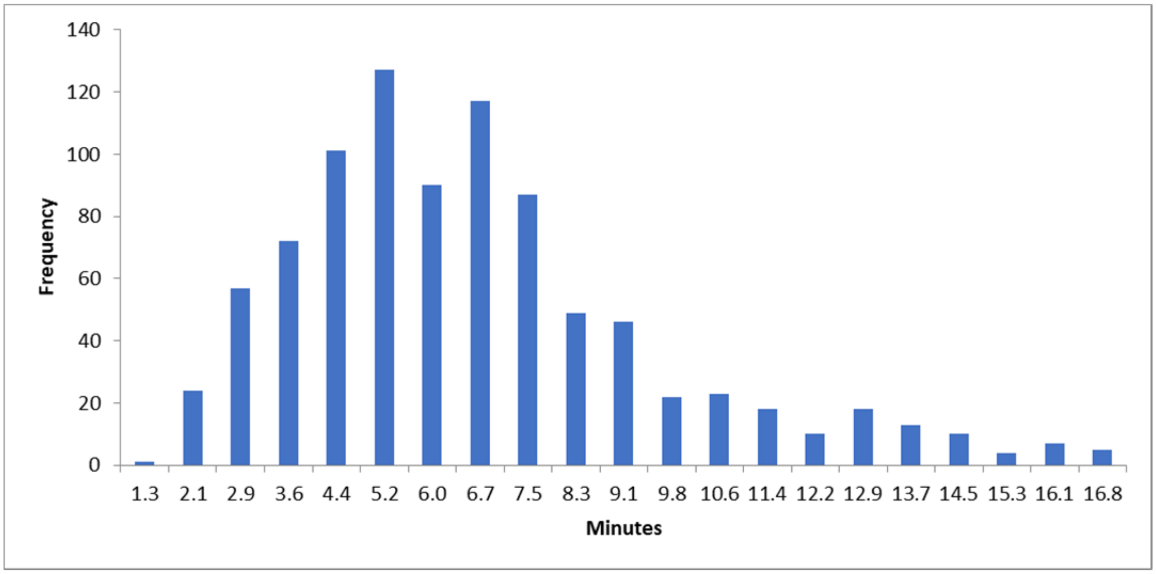


FIGURE 32. DISTRIBUTION OF SIMULATED RESPONSE TIMES, JUNE

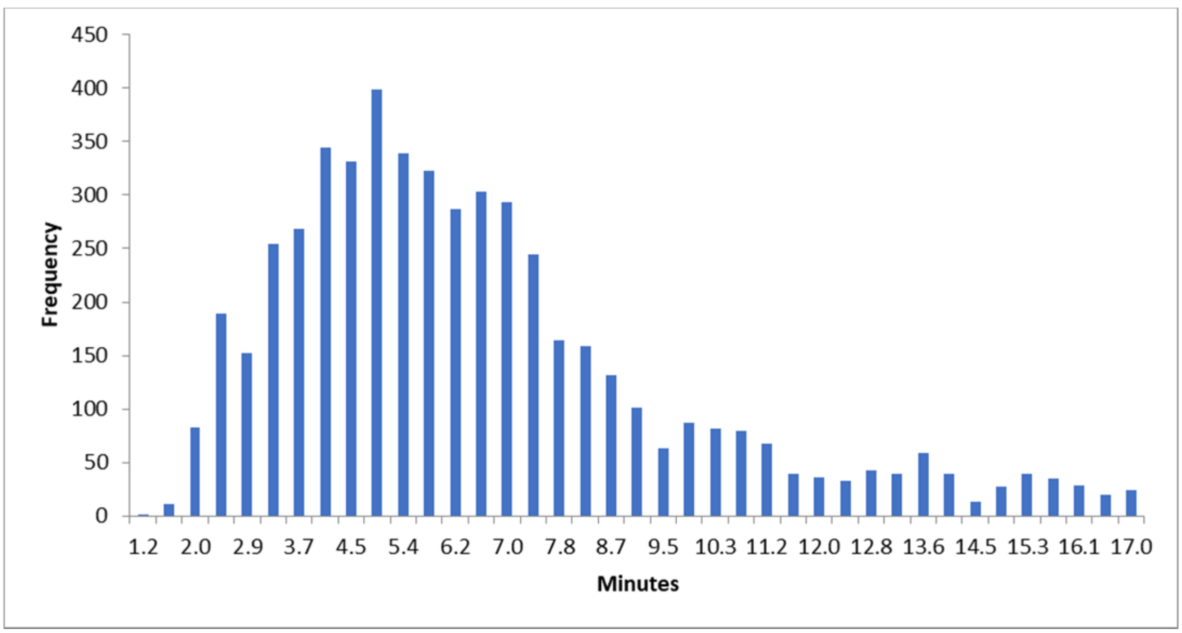


FIGURE 33. DISTRIBUTION OF SIMULATED RESPONSE TIMES, JANUARY–JUNE

By inspection of Figures 27–33, the distributions obtained show just slightly different shapes from one month to the next. Our simulation experiment yielded an average travel speed of 41 km/hr based on the travel time (Arrival Time stamp minus Rollout Time stamp) and the street distance from the responding station to the incident location.

As part of model validation, we summarize in Table 3 the distribution of simulated values of response times, and compare the statistics with those of actual values overall in 2009-2016:

Month	Mean (minutes)	Std Dev (minutes)	Max (minutes)	Min (minutes)	n
January	6.31	3.17	16.8	1.2	873
February	6.42	3.26	16.8	1.5	796
March	6.29	3.19	16.9	1.6	891
April	6.39	3.2	16.9	1.3	884
May	6.44	3.17	16.9	1.4	885
June	6.29	3.03	16.9	1.3	904
Overall (180 replications)	6.36	3.17	17	1.2	5,233
Overall (actual values)	5.74	2.32	17	1	80,310

TABLE 3. STATISTICAL COMPARISON OF SIMULATED VS. ACTUAL RESPONSE TIME DISTRIBUTIONS

On average, our simulation yields longer response times (the difference between overall means is slightly over 37 seconds), and exhibiting greater variability. This may indicate the need for a more sophisticated model for responding vehicles' speeds for incidents located in the more 'rural' areas (with longer travel distances and possibly higher average speed as compared with the more urban areas).

Besides the analysis of the response time, the model allows the generation and collection of other relevant operational indicators (e.g. travel distance/time, workload distribution, etc.). In Figure 34, for instance, we present the average total travel distance for first responding units. The simulated distribution of incidents among the different regions within the city of Vaughan is shown in Figure 35. In Figure 36, we see the breakdown of responding vehicle/crew overall time into APPTOT, Travel, and On scene times.

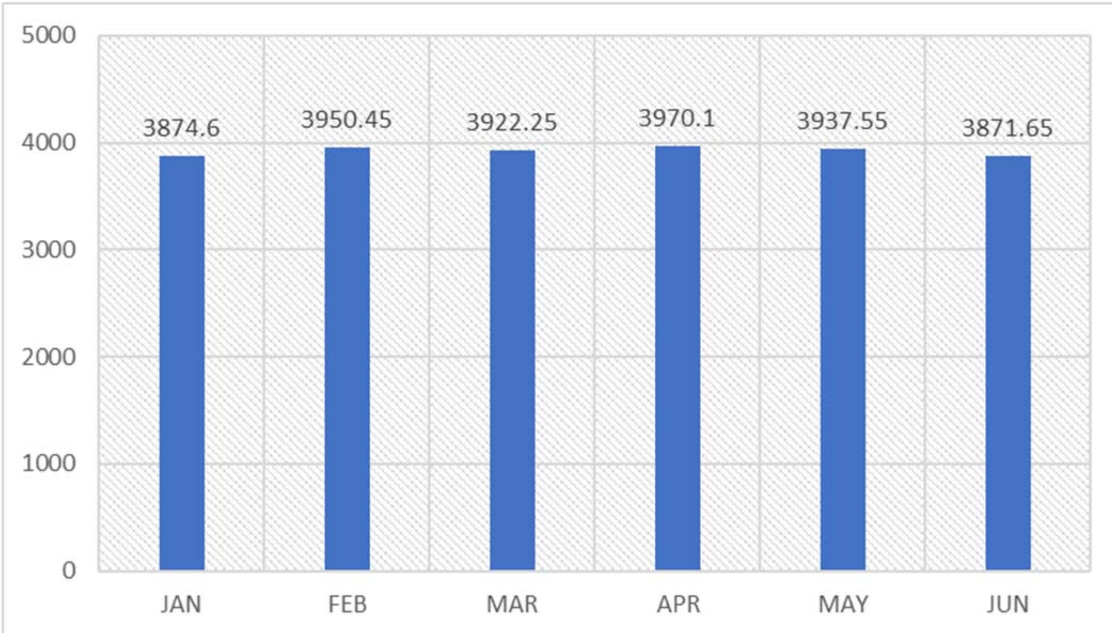


FIGURE 34. AVERAGE TRAVEL DISTANCE PER INCIDENT (IN METERS) FOR FIRST RESPONDER VEHICLES (180 REPLICATIONS)

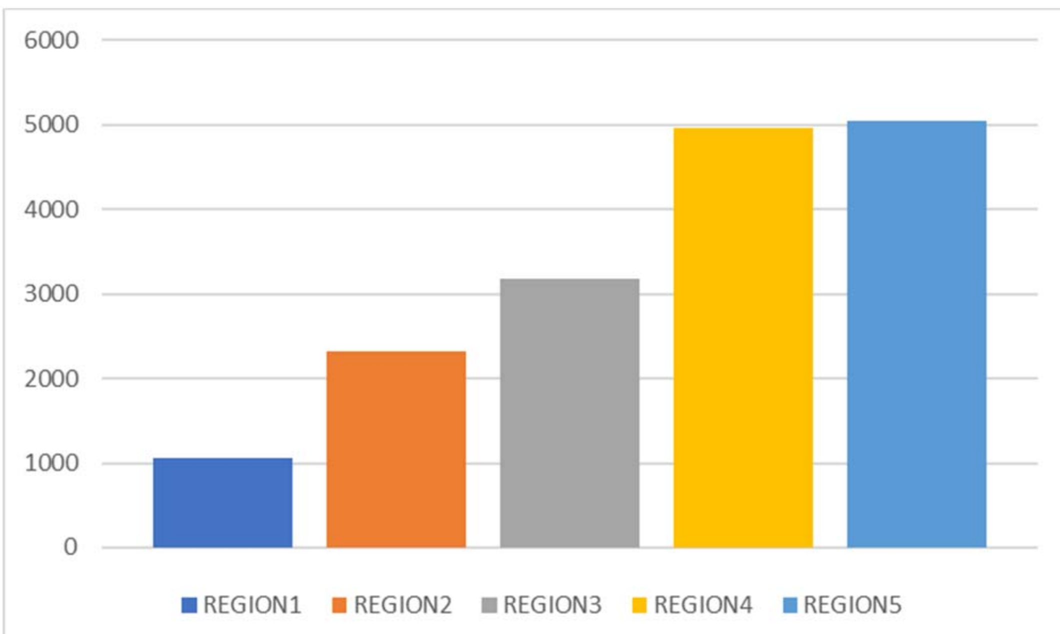


FIGURE 35. SIMULATED NUMBER OF INCIDENTS, BY REGION (180 REPLICATIONS)

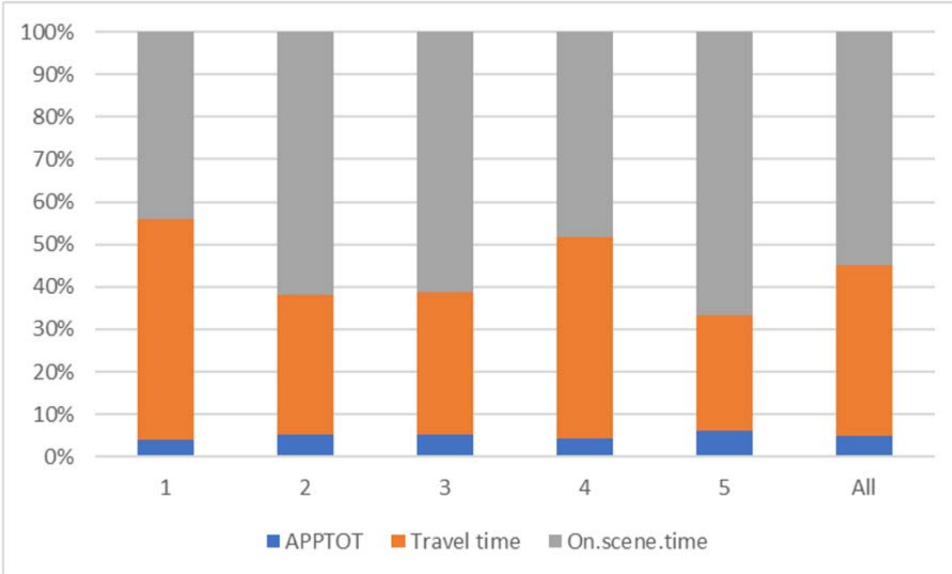


FIGURE 36. RESPONDING VEHICLE/CREW OVERALL TIME BREAKDOWN, BY REGION (180 REPLICATIONS)

Conclusions and Further Research

The current Incident Generation Engine involves stochastic modelling and simulation of the occurrence of incidents (as specified in terms of incident type, 'arrival' time, location, APPTOT, and on scene time). In spite of the inherent variability/uncertainty in observed values, our incident generation model appears to provide simulated response times that more or less follow the actual patterns arising in the historical data. However, the model still needs to be calibrated to further validate resulting distributions of incident attributes in relation to actual distributions.

The simulation produced by means of the two models (Incident Generation Engine and Response Simulation Model) as developed is capable of reproducing the performance of the system. Deviations observed for the experiment (180 replications each having a duration of one day) come mainly from the necessity of calibrating the model (for instance, fine tuning of some parameters such as average vehicle speed).

The Response Simulation Model is intended to provide a flexible tool for planners and decision makers to evaluate various operating scenarios or alternative procedures/protocols – e.g., different numbers, types or allocation of resources, expected demand fluctuations, alternative assignment rules, among others.

EXTENSION AND IMPROVEMENT OF THE DEVELOPED MODELS

We are currently concluding an extended experiment consisting of 365 replications (or the equivalent of one year of emergency incidents and response operations) and will subsequently report on results.

Based on the initial results obtained, further work may include extending the simulation models to enable:

- Definition in the Response Simulation Model of different types of responding vehicles, and establishing protocols for assignment of different types/numbers of responding units depending upon the type of incident.
- Developing more extensive experiments to evaluate different scenarios – e.g., impact of resource demand fluctuations on response times/capacity, comparison between assignment of responding units according to responsible district/region vs. geographically closest station(s).

Acknowledgment

This work was supported by a grant from the Canadian Association of Fire Chiefs (CAFC).

The research team wishes to acknowledge partial financial support from Professor Jianhong Wu, University Distinguished Research Professor and Canada Research Chair in Industrial and Applied Mathematics, of York University.

We are deeply indebted to Chief Larry Bentley, Deputy Chief Deryn Rizzi, Deputy Chief Andrew Zvanitajs, and Captain Kevin Plested of the Vaughan Fire and Rescue Service, not only for making available their incident dataset over the eight-year period from January 2009 to December 2016, but most especially for providing their assistance, guidance, and insights in our statistical analysis of the VFRS dataset and the necessary verification/validation/accreditation of our simulation models.

References

1. AnyLogic Simulation Software, 2017. [Downloadable at http://www.anylogic.com].
2. Calgary Fire Department Annual Report 2011.
3. Calgary Fire Department Annual Report 2016.

4. Canadian Centre for Justice Statistics, 2017. *Fire Statistics in Canada, Selected Observations from the National Fire Information Database 2005 to 2014*. Report prepared for the Canadian Association of Fire Chiefs, September 2017.

5. CPNTools, 2017. [Downloadable at http://cpntools.org/].

6. Fraser Institute Research Bulletin. *Municipal Fire Services in Canada: A Preliminary Analysis*, May 2015.

   [Available online at https://www.fraserinstitute.org/sites/default/files/municipal-fire-services-in-canada.pdf (accessed on Dec 22, 2017).]

7. Ottawa Fire Services 2011 Annual Report.

8. Ottawa Fire Services 2016 Annual Report.

9. Toronto Fire Services 2011 Annual Report.

10. Toronto Fire Services 2016 Annual Report.

11. Vaughan Fire & Rescue Service 2011 Annual Report.

12. Vaughan Fire & Rescue Service 2016 Annual Report.

Author Biographical Information

The research project team is composed of researchers who are affiliated with the School of Administrative Studies and the Advanced Disaster, Emergency and Rapid Response Simulation (ADERSIM) program at York University. The Disaster and Emergency Management graduate and undergraduate programs of York University are housed in the School of Administrative Studies.

Dr. Adriano O. Solis is an Associate Professor of Logistics Management and Decision Sciences and currently the Director of the School of Administrative Studies at York University. He teaches and conducts research in the areas of operations/logistics/supply chain management and decision sciences. He is a member of the graduate faculty in Disaster and Emergency Management, and is an active collaborator in the ADERSIM program. His research interests are in inventory systems modeling, supply chain management, intermittent/lumpy demand forecasting, applied modeling and simulation, and IT in operations and supply chain management. He has served as Program Chair of the Summer Computer Simulation Conference of the Society for Modeling & Simulation International (SCSC 2013, Toronto, Canada) and as General or Program Co-Chair of the International Conference on Modeling and Applied Simulation (MAS 2014, Bordeaux, France; MAS 2015, Bergeggi, Italy; MAS 2016, Larnaca, Cyprus; MAS 2017, Barcelona, Spain). He will serve as General Co-Chair of MAS 2018 in Budapest, Hungary (September 2018). Professor Solis holds BSc and MSc degrees in mathematics, an MBA, and a PhD in Management Science. Before joining York University, he was Associate Professor of Operations and Supply Chain Management at the University of Texas at El Paso. He has been a Visiting Professor at the University of Calabria (Italy), where he has continued to supervise management engineering graduate students in their research work. His teaching is enhanced by industry experience, including having been Vice President and Division Manager for Professional Products and Systems in the Philippine operations of Philips Electronics, the Netherlands-based multinational company.

Dr. Ali Asgary is an Associate Professor of Disaster and Emergency Management in York University's School of Administrative Studies. He is a Principal Investigator and Program Lead for York University's ADERSIM program. He is an expert in disaster, emergency, and business continuity management. His extensive research and effective teaching are enhanced by his active contributions to the profession and by translating them into real world practices at different levels. His research has been funded by SSHRC, NSERC, GEOIDE, PreCarN, AIF, YUFA, and others. He is the author or co-author of numerous scholarly and practitioner articles in disaster and emergency management, and his work has been extensively cited and referenced by other researchers. Professor Asgary has received various awards for his research, teaching and other contributions, including the International Association of Emergency Management Award and the outstanding paper of the year award by the Journal of Disaster Prevention and Management. He obtained his PhD at University of Newcastle Upon Tyne in England. He was one of the faculty members who established the disaster and emergency management discipline in Canadian universities, including York University and Brandon University.

Dr. Jenaro Nosedal is a Post-Doctoral Visitor at York University's School of Administrative Studies and its Disaster and Emergency Management program, and an ADERSIM collaborator. He is course director in Operations Management and Quantitative Methods in Business at the School of Administrative Studies. He holds bachelor's and master's degrees in Industrial Engineering, and received his PhD in Telecommunications and Systems Engineering from the Autonomous University of Barcelona in 2016. Dr. Nosedal's general area of research is in operations and logistics management, specializing in systems modeling and simulation.

Ms. Beatrice Zaccaro holds a Laurea in Ingegneria Meccanica (bachelor's degree in Mechanical Engineering) and is currently a student in the Laurea Magistrale in Ingegneria Meccanica (master's degree in Mechanical Engineering) program at the University of Calabria in Italy. In Fall 2017, she was an International Visiting Research Trainee (IVRT) in the graduate program in Disaster and Emergency Management at York University. Her research interests include modeling and simulation with applications in logistics and in safety and security in industrial plants.

List of Tables and Figures

TABLES

FIGURES

UNIVERSITY OF THE FRASER VALLEY
CENTRE FOR PUBLIC SAFETY & CRIMINAL JUSTICE RESEARCH

YORK UNIVERSITÉ UNIVERSITY
School of Administrative Studies