Design of a Real-Time Emergency Response System For Highway Networks Experiencing a High Frequency of Traffic Emergency Events During Peak Hours

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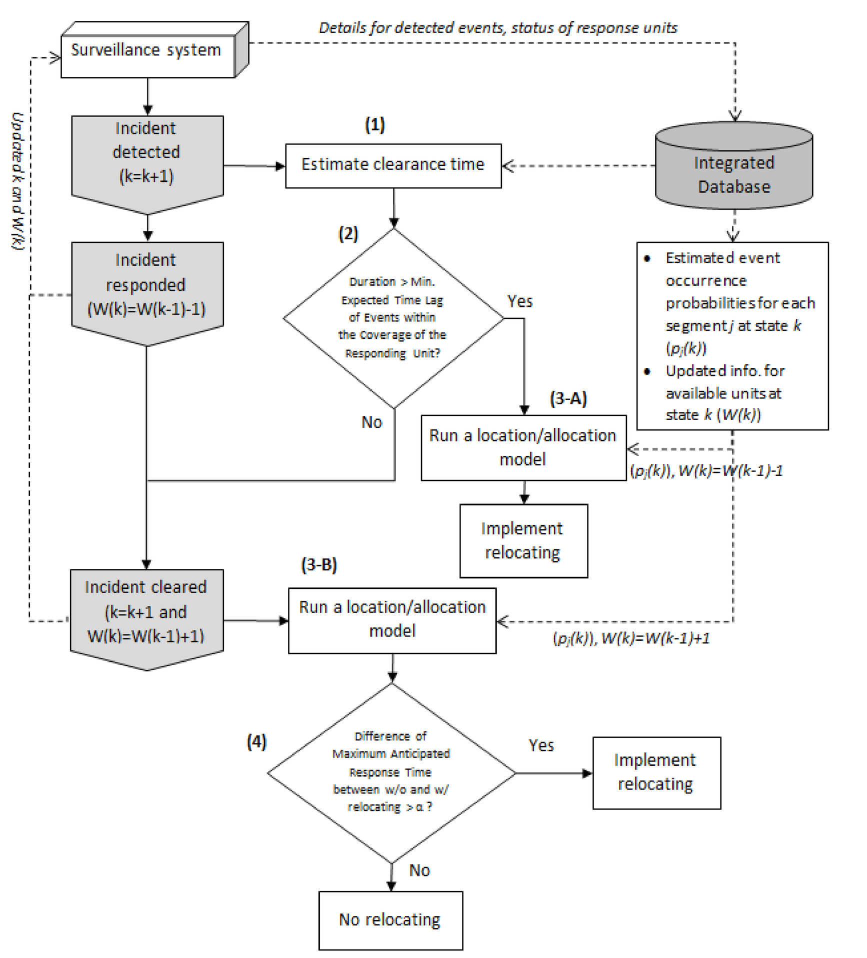
Abstract

- This study proposed a general framework of real-time emergency response operations for highway networks experiencing a high frequency of concurrent traffic emergency events.
- The proposed system consists of three principal models, working collectively for estimating the probabilities of event occurrences, projecting the incident clearance time, and optimizing the location and coverage of available response units.
- The system is designed to assist responsible agencies in assessing the need to relocate available incident response units in real time operations, based on the available resources and detected traffic information.
- The empirical evaluation results showed that the dynamic real-time dispatch strategy can outperform the static dispatch and state-of-the-practice patrolling strategies with respect to minimizing the network-wide delay induced by events and waiting times of vehicles involved in the events for response.

Proposed System Framework



<Operational Flowchart for the Proposed Decision Support System for Implementing Relocation>

Step 1: Estimate clearance time
- Use a well-calibrated clearance estimation model or historical data

Step 2: Initial assessment
- Compare the operational duration needed for the target emergency unit to respond to the detected event, based on the estimated time for having the next event within its service boundaries
- If the detected event is anticipated to be cleared before the next event, the decision process moves to Step 3-B; otherwise, Step 3-A

Step 3-A: Execute the location/allocation model for relocating the remaining units
- Reassign the coverage for the remaining units, using the location/ allocation model with the updated event occurrence probabilities
- Remaining units can provide prompt services to the coverage area for which the unit currently on duty is responsible.

Step 3-B: Execute the location/allocation model based on the updated predicted probabilities of having next incident or assist request
- Given the occurred event, re-estimate the temporal and spatial distribution of potential future incidents or assist requests
- Execute the location/allocation model with these updated probabilities to perform the second assessment in *Step 4*

Step 4: Second assessment to evaluate the need to redeploy response units based on the results from Step 3-B
- Upon clearance of a detected event, evaluate the need to re-deploy all available units
- Based on the updated probabilities of having the next event in each responsible segment over the specified interval and the maximum anticipated response time difference between without relocating and with relocating

Models Embedded in the System

1. The Probabilities for Event Occurrences
- In this study, it was assumed that the number of traffic emergency events occurring on each segment during a given time interval follow a Poisson distribution
- Once the m[th] event arises at segment i, the probability that additional events may occur at the same segment can be calculated as follows:

$$P_i(X > m) = 1 - \sum_{j=0}^{m} P_i(X = j) \qquad \text{For } i=1, 2, \dots, n \text{ and } m=0, 1, 2, \dots$$

2. Event Clearance Time Estimation Model
- This study used a method of *Random Forests,* an ensemble of un-pruned classification and regression trees (CART) for two clearance time estimation models – one for incidents and the other for assist requests
- For model calibration, the event-related information from the CHART data base was used(e.g., onset timestamp, type of incident/requests for assists, number of lane blockages, location, detection source, types and number of vehicles involved, etc.).
- Each developed model consisted of 300 trees and showed good performance for predicting the clearance times

3. The Location/Allocation Model
- This study aims to optimally allocate available resources by minimizing the estimated external delay induced by the projected event as well as the estimated internal delay for vehicles involved in the event, based on the number of available response units and emergency occurrence rates at state k
  - ❑ the *internal* delay: the elapsed time during which vehicles involved in an event are waiting for arrival of response units
  - ❑ the *external* delay: the additional times experienced by other vehicles in the same network due to the impact of the event

Objective

$$\min_{x,y} \sum_i \sum_j [\beta \cdot x_{ij} \cdot p_j(k) \cdot d_j(t_{ij}) + (1-\beta) \cdot x_{ij} \cdot p_j(k) \cdot t_{ij} \cdot a$$

Subject to

$$① \quad d_j(t_{ij}) = \frac{1}{2} {T_{ij}}^2 (q_j - rc_j)\left(\frac{c_j - rc_j}{c_j - q_j}\right) \qquad \forall (i,j) \in N$$

$$② \quad {T_{ij}}^2 = \begin{cases} (t_{ij} + \overline{CT}_1)^2 + Var(CT_1), & for\ incidents\ (\alpha) \\ (t_{ij} + \overline{CT}_2)^2 + Var(CT_2), & for\ assists\ requests\ (1-\alpha) \end{cases} \qquad \forall (i,j) \in N$$

$$③ \quad \sum_i x_{ij} = 1 \quad \forall\, i \in N \qquad ④ \quad x_{ij} \le y_i \quad \forall\, j \in N \qquad ⑤ \quad \sum_i y_i \le W(k)$$

$$⑥ \quad x_{ij} = [0,1] \quad \forall (i,j) \in N \qquad ⑦ \quad y_i = [0,1] \quad \forall\, i \in N$$

- $G(N, A)$: The responsible network freeways, where *N* and *A* are the sets of nodes (exits) and links (segments).
- i and j: Index for nodes. $i, j \in N$
- k: Index for states that are updated when an event is detected or cleared. $k \ge 0$
- x_{ij}: Binary decision variable, indicating if node *j* is covered by a unit at node *i*.
- y_i: Binary decision variable, indicating if a unit stays at node *i*.
- $p_j(k)$: Normalized event occurrence rate at node *j* at state *k* which is $p_j(k) = P_j(X > m_j) / \sum_{j=1}^{N} P_j(X > m_j)$ where m_j is the total number of events occurring at node *j* until the state *k-1*.
- t_{ij}: Travel time from node *i* to node *j*.
- d_j: Predicted delays from events occurring at node *j*.
- a: Average number of vehicles involved in an event.
- β: Weight to reflect the trade-off of the importance between two conflicting objectives.
- T_{ij}: Incident duration equals the sum of response time and clearance time.
- α: Proportion of incidents to all events occurring on freeway segments.
- CT_l: Clearance times(*l*=1: incidents, *l*=2: requests for assists)
- $\overline{CT}_l$: Average clearance time (*l*=1: incidents, *l*=2: requests for assists)
- q_j: Traffic volume at node *j*. c_j: Capacity at node *j*. rc_j: Reduced capacity at node *j*.
- $W(k)$: Available resources at state *k*.

Experimental Design

- The study site was the highway network on I-695/MD-695 in Maryland, about 50-mile long with 43 exits, and managed by CHART (Coordinated Highways Action Response Team), TOC-4 local center with four response units.
  - This site frequently experiences relatively high frequencies of emergency events during AM peak (e.g., a total of 100 days having at least eight events during AM peak in 2013)
- The proposed model is applied over the responsible network so as to minimize the total delays induced by incidents and requests for assists during AM peak hours (7:00 – 9:30) on September 16th and 17th.
- It is assumed that incidents and requests for assists occurred along the highway segments, and response units are deployed at highway exits for dispatching operations.
- Input data and their sources are as follows:
  - ❑ CHART II Database (data for Years 2012 and 2013) to obtain:
    - Occurrence rate of Incidents/requests on freeway segment i (p_i)
    - Average and variance of clearance times for incidents and requests for assists ($\overline{CT}_k$ and Var(CT_k))
    - Incident occurrence proportion α = 0.723
    - Average number of lane closures to determine the reduced capacity (rc_j)
  - ❑ TMS (Traffic Monitoring System) to obtain traffic volume on freeway segment i (q_i)
- The performance of the proposed real-time dynamic dispatching model is evaluated by comparing with two strategies: (1) static dispatching strategy retaining units' assigned locations and coverage over time, and (2) the experience-based patrolling strategy operated by CHART.

Result analysis

- ***Traffic Emergency Events for the Real-world Application***

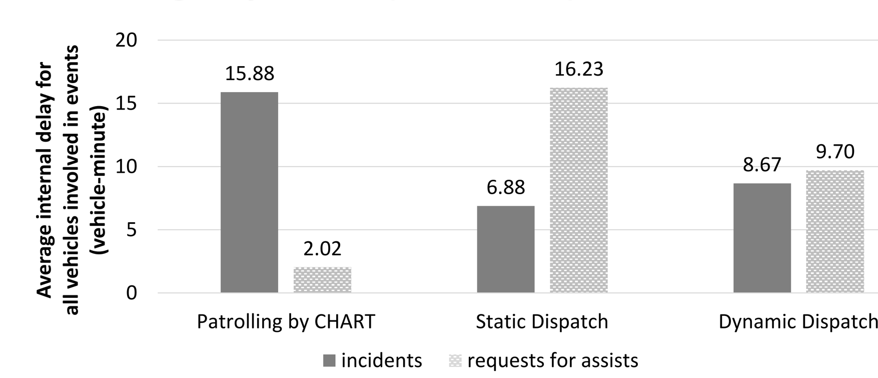
Event ID	Detected Time	Time Lag (min)	Event Type	Location (exit no.)	Direction	Reduced Capacity due to Lane Blockage	Clearance Duration (min)
1	9/16/13 7:39 AM	NA	requests for assists	23	I-695 OL	0.99	2.08
2	9/16/13 7:48 AM	9.22	requests for assists	18	I-695 OL	0.99	5.42
3	9/16/13 7:49 AM	1.05	incidents	29	I-695 OL	0.49	17.69
4	9/16/13 7:59 AM	9.78	requests for assists	19	I-695 OL	0.99	4.68
5	9/16/13 8:02 AM	2.47	requests for assists	18	I-695 OL	0.99	24.80
6	9/16/13 8:09 AM	7.73	requests for assists	19	I-695 OL	0.99	12.82
7	9/16/13 8:23 AM	13.82	incidents	30	I-695 OL	0.83	5.20
8	9/16/13 8:30 AM	7.22	requests for assists	23	I-695 OL	0.99	1.57
9	9/16/13 8:32 AM	1.23	requests for assists	18	I-695 OL	0.99	0.70
10	9/16/13 8:37 AM	5.68	requests for assists	17	I-695 OL	0.99	0.13
Average		6.47	NA	NA	NA	0.92	7.51
11	9/17/13 7:01 AM	NA	requests for assists	10	I-695 IL	0.99	8.05
12	9/17/13 7:01 AM	0.27	requests for assists	17	I-695 OL	0.99	1.70
13	9/17/13 7:38 AM	37.17	incidents	30	I-695 OL	0.49	26.42
14	9/17/13 7:43 AM	4.77	requests for assists	26	I-695 OL	0.99	5.42
15	9/17/13 7:44 AM	0.98	incidents	11	I-695 IL	0.25	67.25
16	9/17/13 8:03 AM	19.27	requests for assists	22	I-695 IL	0.99	14.67
17	9/17/13 8:15 AM	12.02	incidents	26	I-695 OL	0.49	27.12
18	9/17/13 8:39 AM	23.78	requests for assists	22	I-695 OL	0.99	9.48
19	9/17/13 9:02 AM	22.60	incidents	23	I-695 OL	0.13	20.43
20	9/17/13 9:29 AM	27.30	requests for assists	22	I-695 OL	0.99	2.83
Average		16.46	NA	NA	NA	0.73	18.34

- ***Response Performance and the Resulting Delays***

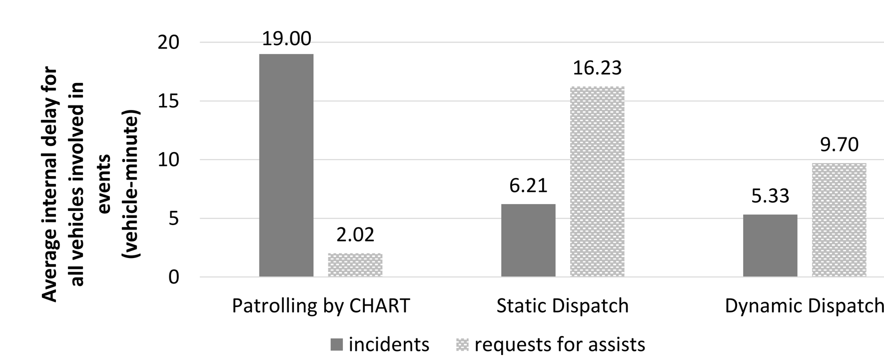
	CHART Patrol		Static Dispatch				Dynamic Dispatch			
Event ID	RT[1] (mins)	Delay (veh-hr)	Dispatched Unit ID	Available number of units[2]	RT[1] (mins)	Delay (veh-hr)	Dispatched Unit ID	Available number of units[2]	RT[1] (mins)	Delay (veh-hr)
1	0.05	-	4	4	3.28	-	4	4	3.28	-
2	3.48	-	3	4	4.66	-	3	4	1.49	-
3*	6.75	91.49	4	3	4.92	78.33	4	3	4.92	78.33
4	0.05	-	3	3	6.10	-	2	3	6.22	-
5	0.07	-	2	2	12.03	-	3	2	2.77	-
6	0.07	-	1	1	17.60	-	1	1	12.34	-
7*	0.20	-	4	2	5.89	-	4	2	14.69	-
8	0.15	-	3	1	12.01	-	3	2	11.71	-
9	0.07	-	4	0	18.89	-	2	1	10.78	-
10	0.08	-	2	0	2.79	-	1	1	1.20	-
11	0.10	-	2	4	1.00	-	2	4	1.00	-
12	0.07	-	3	3	0.75	-	3	3	0.75	-
13*	37.15	377.90	4	4	5.89	97.61	4	4	5.89	97.61
14	3.48	-	3	3	15.07	-	3	3	10.30	-
15*	4.72	8182.63	2	2	2.20	7620.34	1	2	2.20	7620.34
16	0.07	-	1	1	21.50	-	3	2	1.19	-
17*	0.63	250.59	4	2	1.67	269.66	4	2	1.11	259.27
18	0.05	-	3	1	10.21	-	3	2	10.21	-
19*	5.63	1926.34	4	4	3.28	1594.22	4	4	1.26	1334.18
20	8.58	-	4	4	5.49	-	3	4	5.26	-
Avg1[3]	3.57	2165.79	NA	NA	7.76	1932.03	NA	NA	5.43	1877.95
Avg2[4]	1.17	NA	NA	NA	9.38	NA	NA	NA	5.61	NA
Avg3[5]	9.18	2165.79	NA	NA	3.98	1932.03	NA	NA	5.01	1877.95
Avg4[6]	10.98	2165.79	NA	NA	3.59	1932.03	NA	NA	3.08	1877.95

1. *RT* stands for Response Time.
2. *Available number of units* represents that the number of available units at the moment when the corresponding event occurs.
3. ***Avg1* is computed based on data for all events (incidents and assist requests).**
4. ***Avg2* is computed based on data for assist requests.**
5. ***Avg3* is computed based on data for incidents.**
6. ***Avg4* is computed based on data for incidents except Event-ID 7.**
7. An asterisk (*) in ID indicates incident-type of events.

- ***Average Internal Delay for All Vehicles Involved in Emergency Events (in veh-min)***



< Estimations with all events>



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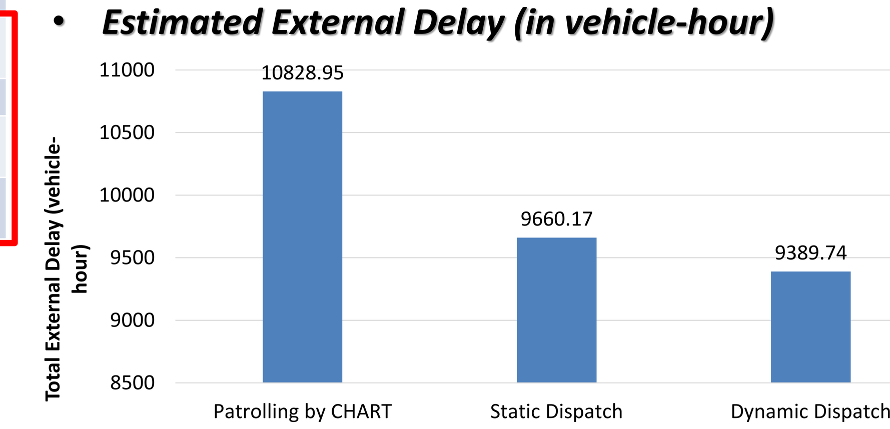
- ***Estimated External Delay (in vehicle-hour)***



Conclusions

- This study has proposed **a real-time dynamic dispatch strategy**, based on the relocating decision support system, consisting of three technical components for consecutively **estimating the probabilities for traffic emergency events, predicting the incident clearance time, and dispatching available response units** – to optimally respond to detected/reported traffic emergency events.
- Since the proposed system is designed mainly for the traffic incident management teams to respond to traffic emergency events, **the system aims to improve the network-wide traffic conditions with a shorter average response time** by accounting for two conflicting objectives.
- The empirical study using CHART II Database has also shown that **the resulting external delays** with the proposed dynamic dispatch strategy are **smaller** than those with the static dispatch and the CHART's patrolling strategies.
- Also, the proposed strategy outperforms the static dispatch strategy and CHART's current practice with respect to **reducing the internal delays, i.e., the duration for those vehicles involved in incidents.**
- Furthermore, the real-time, dynamic dispatch strategy demonstrates more **efficient utilization of available resources** than with the static dispatch strategy, especially when many traffic emergency events may occur in a relatively short time period.