Fleet Optimization for Unmanned Aerial Vehicle-Safety Service Patrol Integration for Traffic Incident Management on Interstates: Insights for Traffic Management Centers

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SHORT SUMMARY

Traffic Incident Management (TIM) is essential for ensuring roadway safety and reducing congestion. However, issues including delayed responses, inefficient resource use, and limited access to incident sites negatively affect TIM. Unmanned Aerial Vehicles (UAVs), offer a viable solution by enabling rapid incident assessment, improving situational awareness, and delivering real-time data for decision-making. This study investigates the design and deployment of UAV-(Service Safety Patrol (SSP) fleet on an interstate by developing an optimization-based framework. Formulated using a 58-mile segment of I-10 in Louisiana, two mixed-integer linear programming models were developed. The objective of the first model was to minimize the number of UAV-SSP units needed to meet a maximum response time threshold, and while the second model sought to minimize the total average response time for a fixed number of units. The results of this study will be used to improve incident response on interstates in Louisiana.

Keywords: Unmanned Aerial Vehicles, Optimization, Traffic Incident Management, Safety Service Patrol,.

1. INTRODUCTION

Traffic incidents remain one of the leading causes of non-recurring congestion on highways, often resulting in significant delays, increased fuel consumption, elevated emissions, and a heightened risk of secondary crashes (Owens et al., 2010). Efficient and timely Traffic Incident Management (TIM) is therefore critical to restoring normal traffic operations, enhancing roadway safety, and improving overall system reliability. While traditional TIM strategies rely on ground-based units such as Safety Service Patrol (SSP) vehicles and roadside surveillance systems, these methods can be limited by delayed detection, restricted field of view, and inefficient allocation of response resources (Kamga et al., 2017).

In recent years, Unmanned Aerial Vehicles (UAVs) have emerged as a transformative technology in the field of transportation, particularly for real-time monitoring and rapid incident assessment (Schultz et al., 2025). UAVs offer several advantages over conventional systems, including flexible deployment, high-resolution imagery, and the ability to access remote or congested areas

quickly (Mohsan et al., 2022). Their capability to provide aerial views of incident scenes can significantly improve situational awareness for traffic management centers, enabling faster response coordination and better-informed decision-making.

The application of UAVs in TIM has evolved from experimental trials to operational pilot programs. Many state DOTs and research institutions have explored their use for traffic surveillance, crash documentation, queue length estimation, and 3D reconstruction of incident sites (Schultz et al., 2025; Alden et al., 2022). With growing affordability and technical capabilities, UAVs have become increasingly attractive to transportation agencies. They provide a unique vantage point for incident assessment and infrastructure monitoring, providing complementary data to traditional sources such as loop detectors, CCTV, and in-vehicle reports. UAVs are especially valuable in areas with limited ground-based sensor coverage or challenging terrain, where conventional response mechanisms are either slow or infeasible.

The benefits of UAVs in the TIM context include improved situational awareness, reduced response and clearance times, enhanced safety for responders and road users, and operational cost-efficiency. UAVs equipped with high-resolution cameras, infrared sensors, and real-time video transmission capabilities enable responders to gain immediate visibility of incident scenes. This allows Traffic Management Centers (TMCs) to assess the scale, location, and nature of incidents particularly in locations without CCTV camera coverage. Real-time aerial views provide critical inputs for dynamic decision-making, such as rerouting strategies, lane closures, and the deployment of appropriate emergency resources.

Additionally, UAVs minimize the need for responders to physically access hazardous or obstructed scenes during the initial investigation phase. This reduces the exposure of personnel to active traffic lanes, fire hazards, chemical spills, or unstable crash environments. Moreover, the use of UAVs in monitoring can deter secondary crashes by providing timely updates and facilitating more effective incident perimeter control. Unlike permanent infrastructure such as surveillance cameras or loop detectors, UAVs offer mobility and scalability. A single UAV unit can be deployed across multiple corridors or event locations, providing a cost-effective alternative to fixed sensor networks. Tethered UAVs further enables persistent monitoring with continuous power supply, overcoming limitations in battery life for long-duration operations.

The integration of UAVs with SSPs is a method that enhances TIM by leveraging the advantages of the two approaches. The mobility of SSP units would ensure that there are mobile patrol units ready to drive to the location of an incident, while deploying UAVs at the scene could enhance situational awareness, efficient resource use and quicker clearance time. This study aims to develop a fleet optimization framework to determine the minimum fleet size of SSP vehicles fitted with UAVs for a section of interstate highway while maintaining effective incident coverage and reducing the total response time based on a minimum fleet size.

2. METHODOLOGY

The fleet size optimization UAV-SSP units consists of two main components: beat configuration, and UAV-SSP unit allocation. Beat configuration defines the geographical boundaries assigned to each UAV-SSP unit, ensuring complete road network coverage. UAV-SSP unit allocation determines the required number of service vehicles, equipped with tethered UAVs, for efficient patrol coverage of designated areas on the interstate.

The freeway network is modeled as a directed graph G (N,A), where N represents nodes (interchanges where UAV-SSP units can turn around), and A represents links $\boldsymbol{l_b}$ (freeway segments) Each freeway segment (i, j) has predefined incident frequency f_{ij} and estimated UAV-SSP travel time t_{ij}. A beat b comprises one or more continuous freeway segments, patrolled by v_b (≥ 1) UAV-SSP units. The entire freeway network is segmented into *B* beats, with a total of *V* SSP units with tethered UAVs, ensuring $V \geq B$.

To ensure efficient coverage, adjacent beats do not overlap, and each UAV-SSP unit is dedicated to a single beat. However, in certain real-world scenarios, short freeway segments may be covered by multiple beats. The study develops two primary objectives to enhance TIM operations:

1. Minimizing the required fleet size – Optimizing the number of UAV-SSP units deployed while maintaining effective incident coverage.
2. Reducing total response time – Ensuring rapid incident response to minimize congestion and improve roadway safety.

Model L1 – Fleet Size Minimization

The objective of this model is to minimize the total number of UAV-SSP vehicles v_b assigned to all beats b. In design of UAV-SSP systems, incident response time is an important performance measure due to its significant impact on incident duration. Response time is defined as the time it takes for a responsible agency (e.g., a UAV-SSP) to detect and respond to an incident after it occurs. Under the condition in which a target response time $\hat{t}$ is given. The goal of model L1 is to minimize the total fleet size of the corridor to generate the operations satisfying the given target response time.

Model L1 (Sun et al., 2018):

$$\textbf{Min} \sum_{b} \boldsymbol{v_b}$$

Subject to Constraints 1, 2, 3, 4, 5, 6, and 7

$$\sum_{ij \in A} \frac{t_{ij} x_{ij}^b}{2 v_b} \leq \bar{t} \qquad \forall b \in \{1,2,\dots,B\} \qquad (1)$$

This constraint (1) ensures that the average response time for each beat b does not exceed the target response time $\bar{t}$. Here, x_{ij}^b is a binary variable that is 1 if link (i, j) belongs to beat b and 0 otherwise.

$$\sum_{ij \in A} t_{ij} x_{ij}^b \leq \hat{t} \qquad \forall b \in \{1,2,\dots,B\} \qquad (2)$$

This constraint (2) makes sure that the total patrol time for each beat b does not exceed the target circulation time $\hat{t}$, where $\hat{t}$ refers to the time it takes for a patrol vehicle to complete a bi-directional circuit (i.e., traveling from the starting point of a beat to the end and then returning to the starting point).

$$\sum_{b} x_{ij}^b = 1 \qquad \forall (i,j) \in A \qquad (3)$$

Constraint (3) ensures that each link (i, j) is assigned to exactly one beat.

$$\sum_{ij \in A} x_{ij}^b \geq 2 \qquad \forall b \in \{1,2,\dots,B\} \qquad (4)$$

Constraint (4) ensures that each beat contains at least two links, maintaining continuity.

$$x_{ij}^b = x_{ji}^b \qquad \forall (i,j) \in A, b \in \{1,2,\dots,B\} \qquad (5)$$

Constraint (5) ensures that both directions of a road segment are included in the same beat.

Model L2 – Total Average Response Time Minimization

This model focuses on minimizing the average response time to enhance the efficiency of incident resolution. When the overall budget is known, the number of available UAV-SSP vehicles can be determined, allowing for the development of an effective patrolling strategy that minimizes response time and maximizes operational efficiency. Model L2 is designed to optimize beat configurations and vehicle allocation, ensuring that the minimum total average response time is achieved while staying within the budget limitations.
Model L2 (Sun et al., 2018):

$$\textbf{Min} \sum_{b} \left(\sum_{ij \in A} \frac{t_{ij} x_{ij}^{b}}{2 v_b} \sum_{i,j \in A} f_{ij} x_{ij}^{b} \right)$$

Subject to constraints 3 to 5.

$$\sum_{b} v_b \leq V \qquad \forall b \in \{1,2,\dots,B\} \qquad (6)$$

The constraints used in L1 were deployed for L2 in addition to constraint 6. Additionally, we define f_{ij} as the incident frequency on segment ij. The expression $\sum_{i,j \in A} f_{ij} x_{ij}^{b}$ computes the total incident frequency of beat b. Consequently, $\sum_b \left(\sum_{ij \in A} \left(t_{ij} x_{ij}^{b} / 2 v_b \right) \sum_{i,j \in A} f_{ij} x_{ij}^{b} \right)$ represents the overall average response time for all incidents along the corridor. The objective of the model is to minimize this total average response time. Furthermore, the constraints related to circulation time requirements and network characteristics remain applicable in this context. The total number of vehicles in the model is limited by the fleet budget V.

Data

The optimization model was applied to a 58-mile section of Interstate 10 (I-10) that spans between Baton Rouge and Lafayette in Louisiana. This corridor includes the Atchafalaya Basin Bridge, a critical elevated section covering several miles over the Atchafalaya Basin, the largest wetland and swamp in the United States. This section of I-10 is a high-traffic corridor, serving as a key connection between western and southeastern Louisiana and facilitating regional freight movement. The roadway experiences heavy daily traffic, including a substantial volume of commercial trucks, making it a strategic location for evaluating SSP deployment. The bridge's elevated structure and lack of alternative routes further emphasize the importance of an efficient incident response strategy to minimize congestion and improve roadway safety. Additionally, this segment of I-10 has multiple interchanges, and key access points to adjacent communities, further influencing patrol beat design.

Ten beats comprising several segments were defined. The beats were defined as the distance between two interchanges where SSP vehicles could turn. This generated segment lengths varying between 0.98 miles to a maximum of 5.78 miles. The speed limit for most of the segments were 70 mph but was restricted to 60 mph on the elevated section. Ten years of incident data was aggregated for each segment with the least number of incidents being 10 and a maximum number of 88 incidents recorded over the period. Another essential parameter in the model design was the travel time t_{ij} for each beat, which was calculated using the segment lengths and travel speeds along the corridor. The travel speed applied in the models was based on the posted speed limits under normal driving conditions. Lastly, constant parameters such as target response time and circulation time were set for 15 minutes and 30 minutes respectively, consistent with the estimated time applied for statewide SSP on-scene time performance measurement during operations in

Louisiana. The available fleet size required in Model L2 is set from the results of the number of UAV-SSP vehicles obtained from Model L1.

3. RESULTS AND DISCUSSION

Table 1 shows the results of the optimization models. The results from Model L1 indicated that a total of **13** UAV-SSP units are required to cover the entire freeway network considered, with each beat assigned a specific number of units based on the length and incident frequency of the segment. The model successfully achieved the target response time of less than 15 minutes, demonstrating its effectiveness in optimizing fleet size without compromising response efficiency.

Table 1. Optimization Outputs per Beat for Models L1 and L2

Model L1 - Fleet Size Minimization				***Model L2 - Total Response Time Minimization***	
b	l_b	Length (miles)	V_b	l_b	Response Time, *T (mins)*
A	[(1,2), (2,3)]	2.48	**1**	[(1,2), (2,3)]	**1.1**
B	[(3,4), (4,5), (5,6)]	3.2	**1**	[(3,4), (4,5), (5,6)]	**3.2**
C	[(6,7), (7,8)]	4.27	**1**	[(6,7), (7,8)]	**2.99**
D	[(8,9), (9,10)]	3.52	**1**	[(8,9), (9,10)]	**1.32**
E	[(10,11), (11,12)]	6.53	**1**	[(10,11), (11,12)]	**3.51**
F	[(12,13), (13,14)]	9.83	**2**	[(12,13), (13,14)]	**2.62**
G	[(14,15), (15,16)]	7.95	**2**	[(14,15), (15,16)]	**3.64**
H	[(16,17), (17,18)]	4.38	**1**	[(16,17), (17,18)]	**1.31**
I	[(18,19), (19,20)]	7.08	**1**	[(18,19), (19,20)]	**4.07**
J	[(20,21), (21,22), (22,23]	9.16	**2**	[(20,21), (21,22), (22,23]	**8.9**
Optimal UAV-SSP Fleet Size			**13**	Total Response Time for all Beats (min.) (Assuming a Fleet Size of 13).	**32.65**
Target Model Response Time (mins.)			**≤ 15**	Weighted Average Response Time (mins.)	**3.52**

The results from Model L2 showed that with a fleet size of 13 units, the total average response time across all beats was **32.65** minutes, with a weighted average response time of **3.52** minutes per beat, which is well below the set target of < 15 minutes per SSP performance measurements. While most beats recorded response times under 4 minutes, Beat J exhibited the highest response time (8.90 minutes). This suggests that further refinement in UAV allocation or additional UAV bases may be required in this beat to ensure equitable response efficiency.

CONCLUSIONS

This study demonstrates the potential of UAVs in enhancing TIM operations, particularly in high-traffic corridors with complex accessibility challenges. By integrating UAVs with SSP units and employing data-driven optimization models, this research demonstrates that incident verification and clearance times can be significantly reduced. The findings show that UAV-equipped SSP

units can consistently achieve response times under 15 minutes, a critical benchmark for preventing secondary crashes and reducing traffic congestion.

Two optimization models were developed to support strategic decision-making in UAV fleet deployment. Model L1 determined the minimum number of UAV-SSP units (13) necessary to cover a 58-mile stretch of I-10 in Louisiana while meeting response time targets. Model L2 refined this deployment by minimizing the total average response time across all beats. However, this technological promise must be weighed against regulatory and operational constraints. UAV deployment in TIM faces several challenges, including FAA Part 107 regulations, which restrict operations beyond visual line of sight and flying over vehicles or people. These limitations may delay UAV deployment during time-sensitive incidents unless agencies proactively secure waivers. To address this, the study recommends streamlined regulatory pathways for UAV use in emergency response contexts.

While offering valuable insights, the study also acknowledges key limitations. The assumption that each SSP vehicle can be equipped with a tethered UAV is currently unrealistic for most agencies due to cost and infrastructure barriers. Additionally, a lack of comprehensive cost data restricted the ability to conduct a full economic analysis.

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