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Optimising Emergency Vehicle Response Times with Genetic Algorithms: Integrating Routing and Traffic Signal Control

Arjun Kulshreshtha
mypublishedpaper@gmail.com
Dhirubhai Ambani International School, Maharashtra

ABSTRACT

This paper explores the potential of genetic algorithms (GAs) in optimising emergency vehicle response times through both dynamic routing and adaptive traffic signal control. Traditional deterministic routing methods, such as Dijkstra's and A*, fail to account for real-time traffic fluctuations or signal coordination, often leading to delays that reduce patient survival rates. A review of existing studies demonstrates that GAs outperform static algorithms by dynamically re-evaluating routes, optimising multi-stop journeys, and scaling to fleet-level management. Similarly, GAs have shown effectiveness in adjusting signal timings at intersections to minimise delays under fluctuating traffic volumes. However, most research addresses routing and signal optimisation separately, leaving a gap in integrated systems that combine both strategies. This paper highlights the need for GA-based frameworks capable of jointly coordinating emergency vehicle routing and signal pre-emption, tested on realistic urban networks. Such integration could significantly enhance emergency response efficiency and provide a scalable, adaptable solution for real-world applications.

Keywords: *Genetic Algorithms, Emergency Vehicle Routing, Traffic Signal Optimisation, Dynamic Routing, Signal Pre-Emption, Urban Traffic Management, Real-Time Optimisation, Evolutionary Computation.*

INTRODUCTION

According to Swan and Baumstark (2021), every additional minute by which ambulances are delayed, the probability of patient survival decreases at an increasing rate. A lot of these delays are a result of traffic congestion or navigation systems ill-suited to adjusting for congestion and signal scheduling.

Traditional vehicle routing algorithms, such as Dijkstra's or A*, operate under static assumptions and are typically not responsive to real-time traffic fluctuations (Vansteenwegen et al., 2011). The route is selected based on available datapoints at the start of the trip, factoring in existing traffic conditions. They however do not account for potential future chokepoints or make any attempt to predict future traffic conditions. They also do not account for other measures that could be used to reduce the response time such coordinating the traffic lights to clear routes for the emergency vehicles. This would not only involve pre-empting them with green lights but also ensuring that existing traffic is cleared out of an intersection before an emergency vehicle even approaches it, ensuring that it doesn't need to slow down or halt at intersections. Similarly, most infrastructure for traffic signal optimisation relies on fixed schedules from pre-optimised systems, making it incapable of responding effectively to emergency scenarios (Teklu et al., 2007).

The ideal solution for this problem is highly challenging to find, however evolutionary algorithms have proven highly effective in such applications, where they are used to develop progressively better solutions rather than attempting to find the best case. Genetic algorithms are one such evolutionary algorithm, none for being highly effective with problems involving numerous interacting variables where the ideal solution is extremely computationally expensive to find. They have proven to be particularly useful when the ideal solution can be sacrificed for a shorter computing time and the priority is to ensure minimum delays rather than just finding the optimal route. There is much existing research in the use of Genetic Algorithms in the field of traffic. Patrascu, Constantinescu, and Ion (2018) discussed how GAs can be effectively used to manage the flow of traffic by optimising the duration of the red-yellow-green phases of traffic lights and how these can then be made responsive to emergency vehicles allowing them to pass through intersections relatively unimpeded. This allows emergency vehicles to reach destinations quicker, while also ensuring that other vehicles can pass through with minimum delays.

This paper reviews existing work to understand the potential of genetic algorithms in this field. It hopes to study how they can be used to optimise the transit time of emergency vehicles by ensuring that they not only follow the most optimal path but also ensuring that traffic along the path is cleared by strategically changing traffic lights and altering street traffic patterns to ensure minimal journey disruption. This study aims to explore genetic algorithms as means of jointly optimising both dynamic routing and traffic signal control, with the goal of minimising emergency vehicle journey times.

Background

The genetic algorithm (GA) is defined as a probabilistic search algorithm inspired by natural selection, commonly used to optimize solutions to problems by iteratively evolving a population of potential solutions through processes such as selection, crossover, and mutation (Urbanowicz and Moore 2013).

A GA works by encoding possible solutions into numeric sequences known as genomes. A random population of several of these genomes is then generated automatically. A fitness function will then be applied to this generation of genomes, and those with the highest fitness score will be allowed to survive to the next generation in a process known as elitism. The fitness function is usually derived from the value that the function is optimising, with larger values corresponding with higher fitness and higher success. Thus, if the aim is to minimise a journey time, its reciprocal would be taken as the fitness function. The individuals that had been selected to survive to the next generation are then allowed to "reproduce" wherein their chromosomes are randomly split and jointed in a process known as cross-over. These chromosomes will also have a small random chance of having some of their values changed to ensure that the solution space is better explored.

Genetic Algorithms for emergency vehicle routing

Many studies have already examined the effectiveness of genetic algorithms in routing emergency vehicles, demonstrating their adaptability and performance across different contexts. For example, Pătrașcu et al. (2018) implemented genetic algorithms to re-assess an emergency vehicle's route in real time by incorporating updated traffic data into their agent-based simulation. Their findings showed that this adaptive approach significantly improved response times compared to generating a single route at the start of the journey with deterministic algorithms. This highlighted not only the advantage of continuous re-optimisation but also the flexibility of genetic algorithms in reacting to unpredictable changes in traffic flow.

Similarly, Geroliminis et al. (2011) applied a genetic algorithm to optimise emergency vehicle pickups during disaster situations. Their work was framed around a variant of the travelling salesman problem, where the vehicle needed to make multiple stops rather than simply travel from one point to another. By addressing this more complex routing challenge, the study demonstrated the ability of genetic algorithms to manage multi-stop, resource-intensive scenarios effectively, a task that deterministic methods would typically struggle to handle. Vitetta et al. (2008) explored a related but broader application, using a genetic algorithm to optimise the pickup paths for a fleet of emergency vehicles instead of focusing on a single vehicle. This extension to the fleet level underscored the scalability of genetic algorithms, showing that they are capable of managing city- or district-wide optimisations where multiple vehicles and objectives must be balanced simultaneously.

Taken together, these studies underline the potential of genetic algorithms not only to optimise and re-assess routes for individual emergency vehicles in motion but also to operate effectively at larger scales. They demonstrate that GAs can compete with deterministic algorithms in both accuracy and computational efficiency, with the added advantage of adaptability to real-time conditions. Moreover, their use in fleet- and city-level routing illustrates that GAs can go beyond isolated vehicle routing and contribute to wider systemic improvements, ultimately maximising efficiency in emergency response.

Genetic Algorithms for traffic light optimisation

Nwiabu and Udoudom (2018) investigated the use of genetic algorithms to optimise the red and green phase lengths of traffic signals at a standard four-way intersection. Their approach allowed the GA to continuously adjust signal timings based on the evolving traffic situation, rather than relying on fixed schedules. The study found that this adaptive method produced a substantial reduction in the average waiting time for vehicles at the signal. This is particularly significant because conventional fixed-time systems are often unable to cope with fluctuations in traffic volume, leading to congestion and inefficient use of the road network. By contrast, the GA was able to dynamically reallocate green time in a way that balanced demand across directions, demonstrating both flexibility and efficiency.

It is important to note, however, that their research did not extend to the prioritisation of emergency vehicles within the signal optimisation process. The focus remained on improving overall vehicle throughput rather than on handling cases where certain vehicles must be granted immediate right of way. Even so, the principles established in this work have direct implications for emergency routing. If GAs can optimise phase lengths to minimise delay for general traffic, then the same adaptability could feasibly be extended to situations where the system must recognise the presence of an emergency vehicle and dynamically restructure the signal plan to prioritise its passage.

Similar studies, such as those by Ceylan and Bell (2004) and more recently Bentaleb et al. (2024), reinforce this conclusion. They consistently demonstrate that GAs are not only capable of reducing average waiting times at intersections but can do so without introducing safety risks such as conflicting signals or unpredictable shifts. Taken together, these studies suggest that genetic algorithms are robust tools for managing traffic signals in real-world conditions. This provides a strong foundation for extending their use to more specialised tasks. Specifically in the case of emergency response, the ability of GAs to handle complex multivariable optimisation problems can be leveraged to ensure that emergency vehicles are able to move uninterrupted across intersections, minimising response times without disrupting traffic flows.

Genetic Algorithms for emergency vehicle routing and traffic light optimisation

Dias (2017) examines the effectiveness of combining dynamic routing algorithms with signal pre-emption strategies to reduce emergency vehicle response times. Unlike static routing, where the path of an emergency vehicle is predetermined at the start of the journey and remains fixed regardless of traffic conditions, dynamic routing continually updates the vehicle's path in response to real-time traffic data.

The study makes it clear that this adaptability leads to far more efficient routing, with dynamic approaches consistently outperforming static ones.

Although Dias does not employ a genetic algorithm specifically, the findings strongly suggest that a GA-based dynamic routing framework would be highly effective. Since genetic algorithms excel at solving optimisation problems with multiple changing variables, their application in this context could allow for even faster and more efficient recalculations of routes as conditions on the road evolve.

The study also highlights the role of signal pre-emption systems, which are designed to adjust traffic signals ahead of an approaching emergency vehicle in order to clear congestion before it arrives at an intersection. This proactive clearing of the path reduces delays that would otherwise occur even with an optimised route. Dias demonstrates that such systems can significantly improve response times, and this offers a clear parallel to the potential of metaheuristic algorithms. A GA, for example, could be integrated not only to find the best route for the emergency vehicle but also to coordinate signal pre-emption across multiple intersections in a way that balances the needs of the emergency vehicle with overall traffic safety. This shows that while the study itself does not implement GAs, it provides a strong case for why they could be particularly effective: they are well-suited to handling the complexity and adaptability required by both dynamic routing and signal pre-emption.

Discussion

The reviewed literature makes it clear that genetic algorithms (GAs) have strong potential in both emergency vehicle routing and traffic signal optimisation, though these two areas are rarely considered together. Most studies focus on one domain at a time, which has produced valuable insights but leaves open the question of how these approaches might work in combination.

In the case of routing, GAs repeatedly show advantages over static deterministic methods. Static approaches typically assume fixed travel times and predetermined routes along with set traffic, meaning they cannot adapt when traffic conditions change unexpectedly. This rigidity is especially problematic in emergency responses, where circumstances are highly unpredictable and likely to change. Road closures, traffic jams, or even small delays can cascade into significant increases in response times. GAs, by contrast, can re-evaluate routes dynamically, updating as per new information that becomes available. Research by Pătrașcu et al. (2018) and Vitetta et al. (2008) highlights this quality. They demonstrate that GAs are not merely effective at optimising a single vehicle's path but are capable of scaling up to coordinate entire networks, something particularly relevant for time-critical emergencies where multiple services may need to be dispatched simultaneously.

In the space of traffic signal control also the literature could not be more clear. Studies such as Ceylan and Bell (2004) and Nwiabu and Udoudom (2018) show that GAs can be used to fine-tune red and green phase timings in a way that reduces average delays and increases throughput at intersections. In other words, they make intersections more efficient for general traffic flow. However, even these studies fail to account properly for emergency services. Optimising for general efficiency means spreading green time in a way that benefits the largest number of vehicles, while emergency response often requires prioritising a single vehicle or lane. This trade-off is rarely addressed in GA signal studies, which means their impressive results for everyday traffic cannot be directly translated into emergency contexts without modification.

The real challenge lies in the joint optimisation of routing and signal control. Dias (2017) demonstrates the promise of this idea through dynamic routing combined with signal pre-emption, showing that clearing intersections ahead of an emergency vehicle dramatically reduces delays. Yet this study, like most others that combine the two, does not use a GA. The few integrated systems that do exist hint at significant benefits but generally stop short of testing GA-based frameworks, which are well-suited for this kind of multi-layered optimisation. Coordinating routing and traffic signals in real time is not a trivial task. Altering the length of the green phase at one intersection can ripple across the network, changing which routes are viable several streets away. GAs, with their ability to balance competing objectives and explore a wider solution space, have the ability to factor in all of these variables and ensure minimal disruption.

Another common limitation in a lot of literature is the use of oversimplified models or simulations. Many studies rely on small-scale, stylised networks such as perfect grids or lightly congested intersections, which strip away the unpredictability of real cities. Pedestrians, cyclists, buses, and mixed-traffic conditions are often absent, and factors such as multi-agent coordination (where several emergency vehicles might need to be dispatched at once) are ignored. This makes results less generalisable. A GA that works well on such a model network may be unable to perform in a real city, where congestion patterns are irregular and often unpredictable. The lack of large, realistic testbeds leaves a gap between promising academic results and real-world deployment.

Taken together, these observations show that while GAs have significant promise in both domains independently, there are no solutions that are effectively able to leverage the strengths of these algorithms to effectively coordinate and optimise the response timing and route of emergency vehicles. This remains a major research gap. Future work could aim to design GA-based systems that explicitly prioritise emergency vehicle response by synchronising real-time route optimisation with adaptive signal pre-emption. Such systems would need to be tested not on idealised grids but on realistically modelled urban networks that reflect the variability of actual cities. Only then can we determine whether the adaptability of GAs can translate into tangible improvements in reducing emergency response times.

CONCLUSION

Genetic algorithms have consistently proven to be powerful tools for both emergency vehicle routing and traffic signal optimisation, particularly in environments where traffic conditions shift rapidly and unpredictably. The literature shows that GAs often outperform deterministic methods by adapting in real time and pursuing solutions that are "good enough" under evolving conditions, rather than relying on rigid pre-computed plans. However, most existing research treats these problems in isolation, focusing either on optimising traffic lights or on routing emergency vehicles. The few studies that attempt to address both simultaneously tend to rely on traditional deterministic approaches rather than metaheuristics.

This leaves a clear gap in the literature. Real-world emergencies demand that routing and signal pre-emption be handled together, since the effectiveness of one depends directly on the other. Current evidence strongly supports the idea that GAs are well-suited to this type of joint optimisation, offering adaptability, scalability, and the ability to handle the complexity of real-time decision-making across a network. As such, there is considerable justification for pursuing GA-based frameworks in this space, and a strong basis to assume that they could significantly improve emergency response times when applied in integrated systems.

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