

System Analysis Document: Intelligent Traffic Management System (ITMS)

***Students, Inc.***

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| 0.4 | Vladislav | 2023-12-05 | Dividing of the former SDD into two separate documents: analysis and design document | *Draft* |

Table 1. Version history

|  |  |
| --- | --- |
| Abbreviation | Meaning |
| SDD | System Design Document |
| SAD | System Analysis Document |
| PP | Project Plan |
| ITMS | Intelligent Traffic Management System |
| STS | Smart Traffic Signal |
| UC | Use case |
| S | Scenario |
| UR | User requirement |
| FR | Functional requirement |
| NFR | Non-functional requirement |
| SSD | State Sequence Diagram |
| SD | State Diagram |
| UCD | Use Case Diagram |

Table 2. Terms and Abbreviations

# Introduction

## Problem Statement: Challenges in Contemporary Traffic Management Control Systems

Traffic management control systems represent a critical civic infrastructure that strives to coordinate and optimize the flow of vehicles and pedestrians to enhance road safety and minimize congestion. However, the inefficacies and limitations present in traditional systems have necessitated an urgent re-evaluation and reconfiguration of already existing frameworks. This problem statement covers the myriad of challenges plaguing contemporary traffic management control systems, providing the necessary context for introducing the Intelligent Traffic Management System (ITMS) as a viable solution.

### Efficiency Constraints

Traditional traffic management systems are often predicated upon static models, operating on a pre-set timing schedule than accommodating to real-time traffic conditions. These models are poorly equipped to adapt to rapid urban growth or dynamic traffic patterns. The limitations of timer-based signals become glaringly apparent during time-bound scenarios where the incoming traffic deviates from interval norms. For example, during non-peak hours, roads remain clear, yet signals continue to follow their pre-set schedules, or in some intersections during busier times, queuing through traffic lanes must wait for empty side lanes, enhancing the already present traffic congestion.

To summarize, the congruence between system capacity and actual road usage remains elusive, creating bottlenecks and contributing to traffic congestion.

### Data Inconsistency and Lack of Integration

In classical (large-scale) traffic management systems, different components such as cameras, speed sensors, emergency systems and other functionalities that manage various aspects of traffic flow often operate in what is called a "silo structure". Individual components operate autonomously, often with limited interaction or data exchange with other units in the ecosystem. Various challenges include, but are not limited to:

* Individual adjacent traffic junctions do not share information between themselves, limiting their potential in various applications, like the optimization of traffic flow between intersections by anticipating shared respective states (e.g., green waves[[1]](#footnote-2)), useful data collection for outside systems, like data collection and manual overview centers, navigation systems and autonomous driving vehicles using real-time traffic data as input.
* Speed sensors may collect valuable data, but when this data is not integrated with information from traffic cameras and navigation systems, their full realizable potential is drastically limited.

Figure 1. A Dutch ambulance responding to an emergency call having crashed on an intersection (DPG Media, 2023)

* The inability of present systems to provide real-time guidance to emergency vehicles can delay crucial medical and security interventions and cause dangerous traffic interactions on intersections, consequently impacting the safety of individuals in need of emergency care and traffic participants, including the medical personnel.

The presence of silo structures in modern traffic management systems, causing an inconsistent widespread implementation, causes various challenges, each of which hampers the overall efficiency and adaptability of these control systems. The fragmented nature of these technological components can lead to a failure in capturing a holistic view of traffic scenarios, thus limiting a traffic system's adaptive capabilities.

### Economic and Environmental Impact

Inefficiencies in traffic management translate to economic losses in the form of reduced productivity and increased operational costs for businesses. Fuel and battery[[2]](#footnote-3) wastage and emissions from idling vehicles caught in prolonged traffic add significantly to the environmental toll.

### Security Vulnerabilities

Legacy systems, including the "silo-structured" systems lack robust security mechanisms, making them susceptible to physical and cyber-like attacks, that can cripple parts of, or worse, the entire traffic management infrastructure. Any cyber vulnerabilities could result in compromised traffic signals and surveillance systems, allowing unauthorized individuals to manipulate traffic flow for their nefarious purposes

.

## Conclusion: The Imperative for the Intelligent Traffic Management System (ITMS)

It becomes clear from the list of challenges described in the preceding sections, ranging from efficiency constraints and data inconsistencies to environmental repercussions and security vulnerabilities, that the functioning of traditional traffic management control systems is lacking a proper implementation basis. The limitations of existing frameworks not only create bottlenecks and exacerbate traffic congestion but also induce economic inefficiencies and contribute to environmental impact. Moreover, the absence of an integrated, secure system introduces a host of vulnerabilities, thereby endangering public safety and infrastructure security. Within this complex web of interconnected challenges lies the rationale for a transformative solution: an Intelligent Traffic Management System (ITMS).

The most compelling rationales for the implementation of the ITMS lies in its dynamic adaptability. Unlike the rigidness of traditional intersection systems, the ITMS is equipped with algorithms capable of real-time adaptation to fluctuating traffic patterns. This adaptability is particularly significant in the face of the limitations posed by static systems, especially in rapidly urbanizing landscapes with complex vehicular flows. Thus, ITMS eliminates undue waiting times at traffic intersections, thereby significantly ameliorating vehicular congestion, a primary bottleneck in traditional systems.

Designed to meet various requirements, such as adaptability, safety, efficiency, and energy efficiency, the ITMS’s goal is to operationalizes the benefits of technological advancements to create a more harmonious traffic management system:

* **Scalability**: The ITMS is natively scalable and relies on an interconnected structure, therefore breaking down the "silo structure" that has been an impediment in existing systems. ITMS enables seamless communication among sensors, traffic lights, but also between multiple intersections, allowing for the seamless integration of any desired features, like “green wave” systems or any safety features.
* **Adaptability:** The ITMS's real-time response to changing traffic conditions averts the inflexibility of existing frameworks, thereby improving system capacity and road usage.
* **Safety:** By providing robust security measures the ITMS not only ensures the minimization of risks but also improves the efficacy of emergency response mechanisms by limiting the traffic blockage.
* **Efficiency and Reliability**: Through intelligent algorithms that optimize green light durations and sequences, being adaptable to any varying intersection, the system promises a notable reduction in travel time and fuel consumption.
* **Energy Efficiency**: The deployment of energy-efficient hardware and algorithms aligns with global sustainability goals, simultaneously reducing operational costs and greenhouse gas emissions.

In summary, the reconfiguration of existing traffic management control systems is on the first hand about operationally modifying existing traffic management frameworks or subsystems, but the focus would also be laid on points related to socio-economic and environmental impacts. The Intelligent Traffic Management System (ITMS) emerges as a critical and timely solution, proficient in mitigating the issues inherent in traditional systems. Its adoption and successful implementation should thus be prioritized and critically evaluated within the broader context of urban planning and sustainable development.

Finally, it is worth stating, again, that the capabilities of the ITMS go beyond operational or technological fixes. Its implementation should be seen as a significant strategic intervention aligned with broader urban planning and sustainable development objectives. By addressing traffic congestion, improving emergency response times, and enhancing road safety, the ITMS contributes to creating safer, more efficient urban habitats conducive to economic growth and environmental sustainability.

# System contextAfbeelding met tekst, diagram, schets, lijn Automatisch gegenereerde beschrijving

Figure 2. Context diagram that illustrates the dynamic interactions between the system and stakeholders (i.e., drivers, pedestrians, and traffic authorities).

Drivers, those responsible for operating vehicles on the road, benefit from the system's capability to furnish real-time information to enhance their driving experience.

Pedestrians, individuals navigating on foot, experience improved safety and convenience through the system's capacity to adjust traffic signals, ensuring a seamless interaction between pedestrians and vehicular traffic.

Furthermore, the system plays a crucial role in supporting traffic authorities, the entities overseeing and regulating road traffic. By supplying them with comprehensive traffic data, the system aids these authorities in making informed decisions and efficiently managing the flow of traffic on the road.

# System Use Cases

## Introduction

In the sections to follow, the use cases and scenarios accompanying the system design for the ITMS are formulated, providing a robust, flexible and efficient instructional guideline, orchestrating a diverse range of traffic interactions in various depicted environments. This imperative provides a thorough approach to the various use cases that constitute the ITMS, ensuring that its functionality, ranging from the basis of its structure to more advanced features, is covered extensively.

The use cases are structured hierarchically, each of them portraying an intersection, where the ITMS should react and respond to physical stakeholders interacting with the system, like vehicular movements. It would also be good the system to engage with outside systems such as emergency responses and data management systems.

The modularity and the expandatory nature of the use cases allows for a layered introduction of functionalities. They are accompanied by traffic scenarios (or simply scenarios, e.g., S01, S02, ...) that demonstrate the rudimentary rules of traffic management, including but not limited to basic traffic flow and traffic light management. These base scenarios set the foundation upon which additional features and improvements can be incrementally built. Concretely, subsequent use cases would cover scenarios where the system needs to operate at a larger scale and/or needs to take into account varying environmental factors and stakeholder interactions at once.

For clarity, each given traffic environment will have a 3 (group), to which every individual environment is ordered according to their complexity and/or system dependency. Although use cases have their individual upgoing numbering (UCxxx), within each table and between all tables for every scenario, the use cases are presented in a logical sequence that allows for easier understanding and incremental development.

The testability of the use cases is an integral part of the system design. Each scenario is not only designed to show the system's adequate response to varying factors within a use case, but also with a focus on how it can be rigorously tested. Test scenarios are, in its own chapter below, articulated upon the traffic scenarios, ensuring that the system would both be reliable and meets any operational requirements.

## Requirements

In this section all the general requirements for a single traffic instersection are listed, which would be developed within the scope of the project (i.e., Use Case 1 and Use Case 2). In the future, possibly the list of requirements could be extended, and they could be implemented but that is uncertain due to the limited workforce and time constraints.

### User requirements

In the use cases to be executed drivers are the only users of ITMS.

|  |  |  |
| --- | --- | --- |
| Requirement ID | Description | Use Cases |
| UR01 | A user shall be able to pass the intersection, waiting for the shortest possible period, considering the current traffic situation. | UC01 |
| UR02 | A user shall be able to pass the intersection simultaneously with multiple other users. | UC01 |
| UR03 | A user shall be able to pass the intersection in a safe manner. | UC01 |

Table 3. User Requirements

### Functional requirements

|  |  |
| --- | --- |
| FR ID | Description |
| FR01 | The ITMS must be able to detect the presence of vehicles in each lane of the intersection. |
| FR02 | The ITMS must implement a priority system, allowing lanes with a higher number of vehicles to pass first. |
| FR03 | The ITMS aims to minimize the overall waiting time for all traffic participants. |
| FR04 | The ITMS must provide traffic light signals (i.e., green, yellow, and red) that adapt based on real-time traffic conditions. |
| FR05 | In cases of more than one node with equal priority, the ITMS must implement a predefined node prioritization policy. |
| FR06 | The ITMS must be capable of handling multiple scenarios for a given intersection, such as one car at the intersection, two cars at opposite or perpendicular lanes, and queues of cars in multiple lanes. |
| FR08 | By default, every traffic light is red. |
| FR09 | The traffic lights in conflicting lanes (e.g., two perpendicular lanes) cannot be green simultaneously. |
| FR10 | No car must wait more than a maximum waiting period. |

Table . Functional requirements

### Nonfunctional requirements

|  |  |
| --- | --- |
| NFR ID | Description |
| NFR01 | The ITMS should be able to operate reliably and continuously, 24/7, without manual intervention. |
| NFR02 | The ITMS should be scalable and modular, capable of managing intersections of different sizes and complexities (i.e., to be open for extensions in the future). |
| NFR03 | The ITMS should be resilient to network delays or faults, maintaining its operational integrity. |
| NFR04 | The ITMS should be decentralized, capable of operating different nodes simultaneously without one central/administrating body. |

Table . Nonfunctional requirements

## Use Case 1: A Simple Vehicular-Only 4-Way Intersection Environment, No Turning Allowed

Figure 3. Use Case 1.

A cross-section of a road

Description automatically generated

Output sensor (i.e., a button)

Input sensor (i.e., a button)

Internal Area

### Introduction

Initially, a simplified use case environment is constructed that represents a vehicular-only 4-way intersection, serving as a Proof of Concept. This version consists of one intersection with four input lanes, each equipped with a traffic light (i.e., N, W, S and E). The vehicle count per lane is measured by an input and output sensors, simulated by buttons. Traffic lights are identical meaning if a statement is valid for one of them, it applies to the others as well. Additionally, vehicles in each lane can go straight only (i.e., cannot turn left or right). As a result, it is possible for two opposite lanes to be green simultaneously (i.e., when W is green, E can be green too and the same applies for N and S). Furthermore, all vehicles are treated as identical sedan cars (hereinafter referred to simply as “cars”) moving with the same speed to mitigate potential bottlenecks arising from variations in vehicle lengths, widths, and speed.

### Scenarios

Several scenarios were developed for this use case to demonstrate the operation of the system and its robustness and reliability.

|  |  |
| --- | --- |
| **Scenario ID:** S01 | The only car on the crossroad wants to pass |
| **Preconditions** | A car approaching the crossroad is detected in Lane W Area and there are no cars in the other lane areas. |
| **Description** | Traffic Light W turns green, allowing the car to pass. Once the car exits the intersection, the light turns red. |
| **Actor:** | A car in Lane W |

Table 6. Use Case 1, Scenario 1

|  |  |
| --- | --- |
| **Scenario ID:** S02 (extends S01) | A car wants to pass while another one in the same lane is passing |
| **Preconditions** | Between the moment when the car from Scenario S01 is detected and its exit from the intersection, a second car is detected in Lane W Area. |
| **Description** | Traffic Light W remains green to allow the second car to pass. Once the car exits the intersection, the light turns red. |
| **Actor:** | A car in Lane W |

Table 7. Use Case 1, Scenario 2

Scenario S02 ensures that if there are at least two cars in the same lane area (i.e., a queue) and no other cars on the crossroad, all of them are allowed to pass while the traffic light is still green.

|  |  |
| --- | --- |
| **Scenario ID:** S03 (extends S02) | A car wants to pass while consecutive cars in the opposite lane are passing |
| **Preconditions** | While Scenario S02 is happening, a third car is detected in Lane E Area. |
| **Description** | Traffic Light E turns green to allow the third car to pass. Once the car exits the intersection, the light turns red. |
| **Actor:** | A car in Lane E |

Table 8. Use Case 1, Scenario 3

Scenarios S02 and S03 ensure that if there are consecutive cars in two opposite lane areas and no cars in the perpendicular lanes, the cars in the two lanes are allowed to pass simultaneously while their respective traffic lights are green.

|  |  |
| --- | --- |
| **Scenario ID:** S04 | A car wants to pass but is detected after another car in a perpendicular lane |
| **Preconditions** | Two cars approaching the crossroad in perpendicular lanes are detected: the first in Lane W Area and the second in Lane N Area, with the car in Lane W detected milliseconds earlier. |
| **Description** | The car in W is allowed to pass first because it is detected first by the system. After it passes, the car in N is allowed to pass (FIFO[[3]](#footnote-4)). |
| **Actor:** | A car in Lane N |

Table 9. Use Case 1, Scenario 4

|  |  |
| --- | --- |
| **Scenario ID:** S05 | A car wants to pass but must wait several consecutive cars to pass in a perpendicular lane |
| **Preconditions** | Several consecutive cars approaching the crossroad in Lane W Area are allowed to pass because they are detected first. A car in Lane N Area is detected immediately after them. However, while the cars in W are still passing, a new car is detected in Lane W Area. |
| **Description** | Although the new car in W is the last detected, it is allowed to pass before the car in N (and while Traffic Light W is still green). Once it exits the intersection the car in N is allowed to pass. |
| **Actor:** | A car in Lane N |

Table 10. Use Case 1, Scenario 5

Scenario S05 demonstrates that FIFO is not valid all the time – in some cases if there are not too many cars in perpendicular lanes, the ones in the lane that is currently green are allowed to pass before the ones in the lane in red although the latter arrived first.

|  |  |
| --- | --- |
| **Scenario ID:** S06 | A car at the end of a long queue wants to pass, while there is an equivalent queue in a perpendicular lane |
| **Preconditions** | There are simultaneous queues in Lane N and E, each consisting of a continuous flow of cars, and the first car in the queue in Lane N is detected first. |
| **Description** | At the beginning, cars in Lane N are allowed to pass (FIFO). After the maximum waiting period, cars in Lane E are allowed to pass. This alternating pattern continues until the last car in Lane E is allowed pass. |
| **Actor:** | A car at the end of the queue in Lane E |

Table 11. Use Case 1, Scenario 6

|  |  |
| --- | --- |
| **Scenario ID:** S07 | A car at the end of a long queue wants to pass, while there are also two opposite equivalent queues in perpendicular lanes |
| **Preconditions** | This scenario extends Scenario S06 by adding a long queue in  Lane S. |
| **Description** | No matter that there are now twice as many cars in the N-S/S-N flow as in S06, the waiting period for cars in E is the same as in S06. The reason for this is that for Lane E it does not matter how many cars are in the N-S/S-N flow once the maximum waiting period is over. |
| **Actor:** | A car at the end of the queue in Lane E |

Table 12. Use Case 1, Scenario 7

|  |  |
| --- | --- |
| **Scenario ID:** S08 | A car wants to pass, while there are two opposite equivalent queues in perpendicular lanes |
| **Preconditions** | This scenario is like Scenario S07, differing only in the presence of one car in Lane E, not a queue. |
| **Description** | With only one car in E, the waiting period for E is the same as in S07 and is determined by the maximum waiting period. |
| **Actor:** | A car in Lane E |

Table 13. Use Case 1, Scenario 8

The following scenarios are general and do not have a car as an actor. They ensure that in case of an external/unpredictable factor the system continues to work.

|  |  |
| --- | --- |
| **Scenario ID:** S09 | An accident occurs in Internal Area |
| **Preconditions** | The system detects presence of a car (or numerous cars) in the crossroad’s Internal Area for an unusually prolonged period, making it assume a car accident occurred. |
| **Description** | All the traffic lights are turned on red until the physical object(s) in the Internal Area vanish. |
| **Actor:** | - |

Table 14. Use Case 1, Scenario 9

|  |  |
| --- | --- |
| **Scenario ID:** S10 | A node does not work properly |
| **Preconditions** | The system detects that one of the nodes is disconnected. |
| **Description** | As the system has determined that one of the nodes has been disconnected, it makes all nodes blink in yellow while the lost node is connected again. ... |
| **Actor:** | - |

Table 15. Use Case 1, Scenario 10

## A diagram of a network Description automatically generatedUse Case 2: A Vehicular-Only 4-Way Intersection Environment, 3 Lanes Per Direction, Turning Allowed Introduction

Figure 3. Use Case 2.

The second use case, managing a 3-lane, 3-direction intersection, within the ITMS project, showcases a step forward in complexity from the simplified UC1. This environment involves an intersection where traffic is managed in four directions with three lanes for each direction, each designated for left turn, straight on, or right turn (e.g., for direction 1 the lanes are 1.1 – left turn, 1.2 – straight on and 1.3 0 right turn).

In this intersection, vehicles select their lanes prior to entry, with each lane equipped with an input and output sensors (i.e., buttons) and control mechanisms (i.e., traffic lights) in the same way as UC1. The ITMS nodes, communicate to measure vehicle counts and determine the sequence of traffic light changes. They autonomously request permission to transition to a green state, coordinating with other nodes to ensure a synchronized decision-making process during traffic light phases and managing transitions from green to orange and then red. Moreover, the system is designed to minimize the total waiting time at the intersection, balancing the needs of traffic streams.

As in UC1, all vehicles are treated as identical sedan cars (hereinafter referred to simply as “cars”) moving with the same speed to mitigate potential bottlenecks arising from variations in vehicle lengths, widths, and speed.

### Scenarios

This use case accomodates all happy-flow scenarios from UC1 (S01-S08) in the cases when cars move straight without turning, as well as S01-S03 for turning lanes.

|  |  |
| --- | --- |
| **Scenario ID:** S01 | A car is detected simultaneously with another car on another node |
| **Preconditions** | A car is detected in Lane 3.2 (i.e., Node 2 – Lane 2) at the same very moment as another car in 2.2 |
| **Description** | The traffic light at Lane 2.2 turns green first because in “shush situations” predefined node priorities are applied (the lower the node number, the higher the priority in such cases). After it passes, the car in 3.3 is allowed to pass. |
| **Actor:** | A car at 3.2 |

Table 16. Use Case 2, Scenario 1

|  |  |
| --- | --- |
| **Scenario ID:** S02 | A car wants to pass, but it is detected after another car in a conflicting lane |
| **Preconditions** | A car coming from Lane 1.1 is passing the intersection when a second car is detected in Lane 3.2. |
| **Description** | The car in 3.2 waits until the first car has passed, and its respective light becomes red, then the second is allowed to pass. After it passes, its light goes red. |
| **Actor:** | A car at 3.2 |

Table 17. Use Case 2, Scenario 2

|  |  |
| --- | --- |
| **Scenario ID:** S03 | Cars arriving in contradicting lanes, several cars |
| **Preconditions** | There are several cars passing in 1.1, 1.2 and 1.3 and a queue in 3.1. |
| **Description** | Once after all lanes in Node 1 become red, 3.1 goes green. |
| **Actor:** | Cars at Node 1 and 3 |

Table 18. Use Case 2, Scenario 3

|  |  |
| --- | --- |
| **Scenario ID:** S04 | Cars arriving in contradicting lanes, more complex scenario |
| **Preconditions** | There are several cars passing in 1.1, 1.2 and 1.3; queues waiting in 4.1 and 4.2 that came next; queues waiting in 2.1 and 2.2 that came next and and a queue in 3.1 that came the last. |
| **Description** | The execution order would be the following: ... |
| **Actor:** | Cars at Node 1 and 3 |

Table 19. Use Case 2, Scenario 4

|  |  |
| --- | --- |
| **Scenario ID:** S05 | Cars arriving in non-conflicting lanes |
| **Preconditions** | There are several cars passing in 1.2 and 1.3, a queue in 4.3 and a queue in 3.3. |
| **Description** | All these lanes are green simultaneously because there are not in conflict with each other. |
| **Actor:** | Cars at Node 1, 3 and 4 |

Table 20. Use Case 2, Scenario 5

|  |  |
| --- | --- |
| **Scenario ID:** S06 | Cars arriving in non-conflicting lanes, more complex scenario |
| **Preconditions** | There are several cars passing in 2.1, 4.1, 3.3 and 1.3 and queues waiting in 1.1 and 1.2 |
| **Description** |  |
| **Actor:** | Cars at Node 1, 2, 3 and 4 |

Table 21. Use Case 2, Scenario 6

|  |  |
| --- | --- |
| **Scenario ID:** S07 | Light malfunction at Node 3 |
| **Preconditions** | Traffic light issue at Node 3. |
| **Description** | Fail-safe triggers: all nodes blink yellow until node 3 behaves as usual again. |
| **Actor:** | System malfunction (N/A) |

Table 22. Use Case 2, Scenario 7

# References

1. A green wave system allows a system to give traffic in moving lanes multiple succeeding green lines, optimizing their flow as they will move through multiple adjacent intersections without having to stop. [↑](#footnote-ref-2)
2. Electric vehicles still use their electrical batteries while idle for various system tasks, although this loss is generally less than fuel wastage for idling combustion-engine vehicles. [↑](#footnote-ref-3)
3. FIFO – The first in is the furst out. Meaning: the car that came to the crossroad first passes first and each subsequent car passes relative to the time of its arrival. [↑](#footnote-ref-4)