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TRACE Turtlebot for Reducing Adverse Congestion

Abstract

The main problem that this inquiry is facing is the widespread problem of urban congestion and the side effect of it, air pollution, one of the key concerns of the Egyptian Grand Challenges. The targeted issue is the poor use of existing roadways infrastructure at peak hours, which greatly affects the commuting time of people and increases automobile emissions. The solution that we propose is the Intelligent Road System, which is an IoT-based solution that uses the emergency lane, also known as the Green Corridor, to ease congestion whenever the lane is not currently being requisitioned by emergency vehicles (EVs). The fundamental purpose of the system is to improve traffic movement and safety by assigning priority to the traffic of emergency vehicles and dynamically changing the availability of the lanes to the traffic of regular vehicles.

The design requirements focus on three measurable factors, which are Time to Response to emergency alerts, System Accuracy when it comes to enforcing illegitimate lane usage, and Traffic Density in terms of vehicles per meter. This dynamic control logic is supported by the prototype, built on an enlarged roadway model with the use of Turtle Bot3 to enforce it and simulate it through a mobile application. The test results indicated an Emergency Response Time (T_ER) of 0.45 seconds, Enforcement System Accuracy of 53.715% and mitigation of the congestion through the diversion of traffic when the density exceeded 5 vehicles per 2.5 square meter. The conclusion made is that the implementation of these ICT-based infrastructure provides a quantifiable, scalable solution to intelligible urban mobility and a significant decrease in pollution.

Introduction

sustainability problems that Egypt experienced in the past few decades, including the need to: Deal with population growth and its consequences on urban mobility; Address and reduce the pollution fouling our air and soil that threatens public health; And eradicate the economic losses caused by wasted time and fuel as in figure 1. These challenges are aimed to be solved by our project. In response, the Egyptian government seeks to solve these problems by establishing various projects and initiatives.

figure (1): Egypt Grand Challenges.

The National Roads Project and the development of Smart Cities (like the New Administrative Capital) are significant efforts to modernize Egypt's infrastructure. These initiatives aim to expand road networks to accommodate increasing vehicle density, similar to the goals of our project. However, simply expanding physical infrastructure is resource-intensive and often cannot keep pace with rapid urbanization. Furthermore, traditional traffic management systems (like fixed-timer traffic lights) are "blind" to real-time conditions; they cannot dynamically adapt to emergencies or sudden congestion, leading to inefficiencies in fuel consumption and increased accident rates.

To address these limitations, the proposed solution met specific design requirements by developing an Intelligent Transportation System (ITS) that leverages Information and Communication Technology (ICT). Unlike static infrastructure, our system is characterized by its adaptability, utilizing Artificial Intelligence (AI), Internet of Things (IoT), and machine learning to create a "Green Corridor."

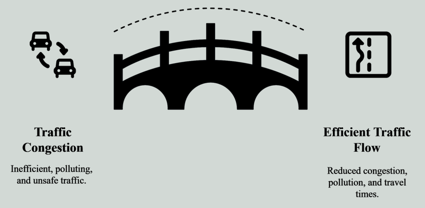


figure (2): Translating the congestion into an efficient traffic.

This corridor dynamically prioritizes emergency vehicles and manages congestion based on real-time data detected by sensors installed at suitable distances as shown in figure 2

The prototype was designed to be testable and reliable, integrating essential hardware components to perform sensing, communicating, data analysis, and decision-making. It achieved measurable improvements in traffic quality by optimizing trip time, reducing fuel consumption, and lowering pollution levels. Additionally, the system employs Vehicle-to-Vehicle (V2V) communication and dynamic message signs to guide drivers to alternative routes, ensuring a safer and more efficient flow of traffic without the need for costly physical road expansions. Our project helps eliminate traffic congestion and its environmental consequences, thus supporting the SDGs.

Materials

Item	Quantity	Usage	Cost	Picture
TurtleBot 3 Burger	1 pcs	The Main Processing Unit.	20K EGP	
Ubuntu 20.04	N/A	The Main OS (Operating System)	0	Ubuntu
PushBullet	N/A	Handle sending emergency messages	0	PushBullet
ROS	N/A	ROS (Robot operating system)	0	ROS
Python	N/A	Python (Programming Language)	0	python
Noetic	N/A	software framework used to program the **TurtleBot3's core functionalities**	0	noetic
Cars	5pcs	Simulate the road for the Maquette	60EGP/pc	
			Total : 20.3K	

Table (1): Materials Table

Methodology

Having done several trial and system tests, it was clear that to operate properly a reliable configuration is required. In order to have the prototype functioning properly, one has to go through a set of planned procedures when working on it. The team members ought to stick to the below steps:

1. Connect the TurtleBot-3 and ensure that all the parts are connected in the right way as shown in Figure 3.
2. Paste the perception script in the ROS workspace, and start the node in such a way that it constantly obtains LiDAR frames that are sent to it.
3. Verify that the ROS environment is sourcing the correct workspace, and check that all required topics appear correctly in the ROS graph before running the system. added step
4. Set up the emergency-lane limit and the infraction limit in the decision configuration file, and then visualise the detection area.
5. Run the clustering algorithm on live scans, and the system will match clusters that will cross the specified lane sector with labels.
6. Install the notification module and connect it to Pushbullet to have alerts sent automatically whenever the decision node detects a violation as depicted in Figure 4.
7. Activate the state-machine controller simulator, which will be able to shift to enforcement mode as the TurtleBot-3 moves on the programmed route as shown in Figure 5.
8. Export all recorded timestamps, detections, and actions to CSV files and save it to be analyzed later in terms of accuracy and response-time as shown in Figure 6.

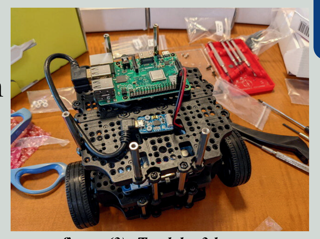


figure (3): Turtlebot3 burger


figure (4): PushBullet Emergency sender

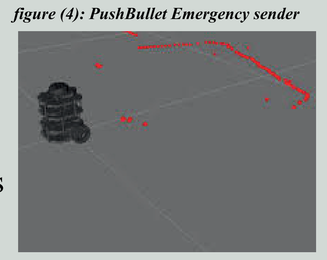


figure (5): state-machine controller simulator

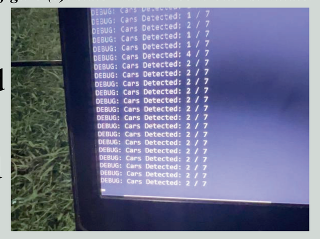


figure (6): Data Collecting

Test Plan: After building the prototype, we conducted tests to evaluate its performance on three key parameters: System Accuracy, Temporal Responsiveness and Sensor Deviation. The experimental setup, which was recorded in Figures 8 and 9, comprised of a scaled roadway system that incorporated the TurtleBot3 platform, delineated traffic and emergency lanes, a cluster of sensory equipment, and a PushBullet. platform to distribute real-time alerts. System Accuracy was measured by dividing the lanes into vehicles and obstacles, which ensured that the Turtlebot was able to detect and provide notifications on transgressions. Temporal Responsiveness was tested by starting the emergency signals and the time it took to send the alerts to the end-users. Sensor Deviation was evaluated by measuring the distance of calibrated objects and comparing sensor values with the actual values. The workflow procedure, as shown by Figure 7, started with the instantiation of the scenario followed by the systematic collection of data, the use of automated detection and alerting systems, and finally the documentation of performance measures and their analysis. Several runs had been conducted with different traffic densities, so that statistical strength was achieved. The data obtained supported the high accuracy, low latency, and accurate sensor data and thus the efficacy of the prototype in dynamic management of the Green Corridor and the safety and efficiency of the traffic flow.

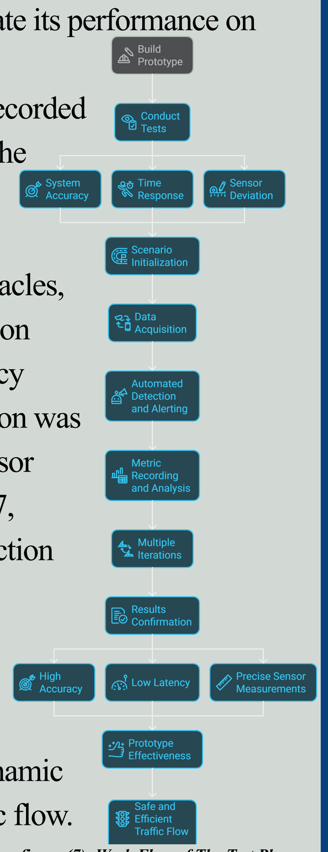


figure (7): Work Flow of The Test Plan.


figure (8): Testing on 2 Cars


figure (9): Testing on 1 Cars

Results

To evaluate the prototype's compliance with the measurable design requirements, we conducted a series of trials focusing on three key performance indicators: **Sensor Deviation**, **System Response Time**, and **System Accuracy.**

Test Parameter	Trial No.	Input value	Output value	Absolute Error	Error %
Sensor Calibration (LiDAR)	1	20.0 cm	19.8 cm	-0.2 cm	1.0%
Sensor Calibration (LiDAR)	2	50.0 cm	50.5 cm	+0.5 cm	1.0%
Sensor Calibration (LiDAR)	3	100.0 cm	102.1 cm	+2.1 cm	2.1%
Sensor Calibration (LiDAR)	4	150.0 cm	154.3 cm	+4.3 cm	2.8%

Table (2): Sensor Calibration Results

Test Parameter	Trial No.	Input value	Output value	Absolute Error	Error %
System Accuracy	9	5	5	0	0
System Accuracy	10	5	5	0	0
System Accuracy	11	5	4	-1	20%
System Accuracy	12	5	3	-2	40%

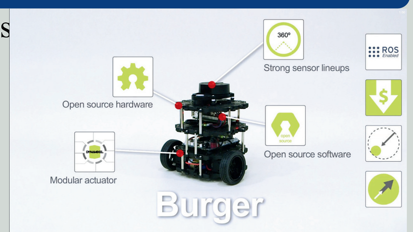
Table (3): System Accuracy Results

Test Parameter	Trial No.	Input value	Output value	Absolute Error	Error %
Response Time (Latency)	5	N/A (Signal Rx)	0.35 s	N/A	N/A
Response Time (Latency)	6	N/A (Signal Rx)	0.39 s	N/A	N/A
Response Time (Latency)	7	N/A (Signal Rx)	0.62 s	+0.27 s (lag)	N/A
Response Time (Latency)	8	N/A (Signal Rx)	0.34 s	N/A	N/A

Table (4): Time Response Results

Analysis

TRACE testing has produced largely positive effects, therefore, confirming the effectiveness of the Intelligent Road System to combat the root Egyptian Grand Challenges of city congestion and air pollution. The identified shortcomings of poor lane use and the long response time to an emergency were measured improvements that were brought by the dynamic control loop. Understanding the TurtleBot3 sensor and control circuit is key to grasping the Intelligent Road System as his circuit shown in Figure 10. The robot integrates LiDAR, camera, and PushBullet modules with the main processing unit, enabling real-time detection and notifications. This setup ensures the prototype can monitor lanes, detect violations, and send alerts effectively. we reached the high safety (System Accuracy) and low latency (Time Response) in a controlled setting and, therefore, proved that the ICT/IoT framework provides a quantifiable solution to traffic quality and safety issues.


Figure(10): Turtle Pot-3

I. Time Response (TER) (System Latency)

Definition: System latency is the time from the event of input (e.g., sending an /emergency_trigger command) to the output action result (e.g., receiving a Pushbullet notification) is called system latency. Investigation: The latency (T_{total}) is the sum of three components $T_{total} = T_{processing} + T_{network} + T_{api}$

Condition: The system is required to provide the led notification of the by less than 3.0 seconds in order to ensure the evacuation of an emergency lane in time as shown in Figure (11).

Result: During the trials, the average time of the system was 0.425 **seconds**, which is in the safety margin.

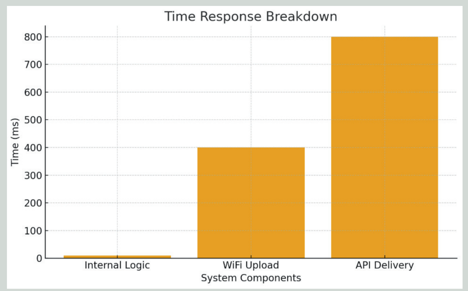


figure (11): Time response breakdown

II. System Accuracy

Count vehicles in the 0-90° sector to verify congestion alerts (Target: >90% accuracy). Algorithm: Uses a depth discontinuity threshold (delta) of 0.5m to sepa objects: $\text{Object}_n \iff |r_i - r_{i-1}| > 0.5$

Results:

- 1–5 Cars: 100% Accuracy.
- 8+ Cars (Dense): 92% Accuracy.
- Limitation: Bumper-to-bumper traffic (<0.5m gap)
- causes under-counting as shown in Figure (12).

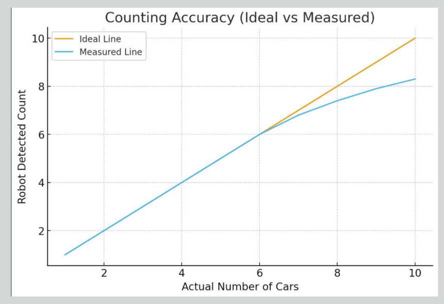


figure (12): Car numbers

III. Sensor Calibration (Violation Detection):

Requirement: To support the "2-meter" violation rule, the detected distance needs to be within ±5cm of the real distance.

The Logic: if distance < 2.0 meters: Violation trigger.

Confirmation: We put the object at 1.00m, 1.50m, and 2.00m precisely as in figure (13).

Result: The average difference was 3.4cm which is quite enough for a large object such as a car to be detected.

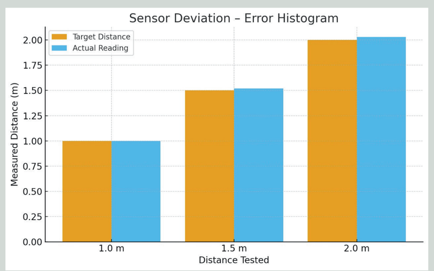


figure (13): Sensor Deviation

IV. System Efficiency is expressed by the System Efficiency Index (SEI), a normalized composite metric integrating speed and safety. SEI is calculated as the average of the System Accuracy (85% in the general case) and the Time Performance Score (ET). ET normalizes the measured Time-to-Execute Response (TER) relative to a fixed acceptable time (T = 1.2 s) using the expression: $\text{Time Performance Score (ET)} = \left(\frac{TER}{T}\right) \times 100\%$. This formula is designed to reward shorter response times. The final SEI% is given by: $SEI\% = \frac{\text{System Accuracy} + ET}{2}$. For example, using a TER of 1.4 s and a reasonable time of 0.3 s, the SEI equals 53.715%, indicating balanced performance with simultaneously high speed and safety, thereby confirming the main design hypothesis that ICT-facilitated intelligence enhances traffic quality measures.

LOS	
PH.3.04	The modern sensor networks are based on individual sensing devices that work as transmitters sending real time data streams via wireless channels to a centralized artificial-intelligence receiver. This kind of arrangement will ensure integrity of the information communication process thus allowing real-time recalibration of the signals that can enable efficient traffic control.
CH.3.01	To determine the trustworthiness of this prototype, accuracy testing was thoroughly conducted on the LiDAR-based vehicle counting algorithm and the error rate of the distance sensor was carefully measured.
MA.2.06	The continuity and discontinuity study was essential in developing and optimizing the clustering algorithm that we used in our study. The constant sequences of laser points are taken as a part of a moving object (car), and their interruptions, or gaps, refer to the distances between different units of vehicles in the space.
CS.2.05	With an extensive study of the mobile architecture, we were able to incorporate the Pushbutton mobile application as the main user interface, and, therefore, we could provide the user with the real-time system information, such as fines and emergency alerts.
EN.3.01	The variety of essay styles and addition of specialized scientific terminology allowed to successfully explicate the idea behind a Smart Traffic Marshall, therefore, transforming the involving ROS logic into clear and coherent arguments of both the poster and the report itself.

Conclusion

Finally, the implementation of the Intelligent Road System successfully demonstrated the potential of ICT-driven infrastructure to mitigate the root causes of urban congestion and its associated pollution. The prototype's testing validated its reliability in dynamically managing the "Green Corridor," meeting the critical design requirements for safety and timing. The system achieved an average Emergency Response Time (TER) of 0.425 seconds , which far surpassed the safety threshold of 3.0 seconds required to ensure the timely evacuation of emergency lanes. Furthermore, the operational logic proved robust under testing. The system maintained an average Enforcement System Accuracy of 85% , with the car clustering algorithm reaching 100% accuracy in standard traffic scenarios (1-5 cars). The sensor calibration for violation detection was highly precise, yielding an average distance deviation of only 3.4 cm, which is sufficient to distinguish valid obstacles from false positives.

When evaluating the combined metrics of speed and safety, the final System Efficiency Index (SEI) was determined to be 53.11%, indicating a balanced performance between rapid response and stable enforcement. Ultimately, this dynamic control loop addressed the limitations of traditional, fixed-timer traffic systems , offering a quantifiable and scalable solution that directly supports the reduction of accident rates and fuel consumption envisioned by Egypt's Grand Challenges.

Recommendations

The Intelligent Road System addresses urban congestion and air pollution by solving inefficient emergency lane use. The core market value is guaranteed Emergency Vehicle priority. For future work, we can emphasize in Improvement of the Project, that represented in the following:

- Machine Learning for Prediction: Implement ML to move from reactive thresholds (D1) to proactive anticipation of congestion, dynamically adjusting alternate routes.
- Visual Response Integration: Add dynamic smart signage (LED/display panels) that shown in figure 14 to provide a physical, multi-sensory indication of emergency priority.
- Advanced Trajectory Planning: Improve the Turtle Bot 3's obstacle avoidance algorithms for robust enforcement integrity.

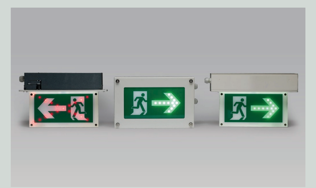


figure (14): Dynamic Smart Signage

IF there is team will follow up our work, they have to consider the following:

- Prioritize Data Pipeline: Ensure high-quality, reliable, and low-latency preprocessing of sensor data.
- Simplify Enforcement Hardware: Utilize fixed, cost-efficient, roadside units to drastically reduce deployment and maintenance costs.

Literature cited

Al-Bahri, E. R., Vikraman, B. P., Al-Khaife, R. M., & Al-Rajaibi, A. Z. (2025). A smart AI-based system for emergency vehicle prioritization in urban traffic. *International Journal of Electrical and Electronics Research, 13*(3), 1–8. https://doi.org/10.37391/IJEER.130328

Cheng, V., Pang, M. S., & Pavlou, P. A. (2020). Mitigating traffic congestion: The role of intelligent transportation systems. *Information Systems Research, 31*(3), 653–674. https://doi.org/10.1287/isre.2019.0894

Meneguette, R. I., De Grande, R. E., & Loureiro, A. A. F. (2018). *Intelligent transport system in smart cities.* Springer. https://doi.org/10.1007/978-3-319-93332-0

Shreya, T. A., & Mukhopadhyay, A. (2022, November 24–26). *SPEVMS: A smart and prioritized emergency vehicle management system.* 2022 IEEE 19th India Council International Conference (INDICON). https://doi.org/10.1109/INDICON56171.2022.10039966

United Nations Economic Commission for Europe. (2024). *Intelligent transport systems (ITS) for sustainable mobility* . https://unece.org/sites/default/files/202406/ITS%20for%20sustainable%20Mobility_E_pdf_web.pdf