

PROBLEM STATEMENT 06:

GPS Toll based System Simulation using Python

Team: Logic loom

Mentor: Dr. Anju Pratap

Member 1: Hima Rose George

Member 2: Anjitha Anil

Member 3: Ashwini Anil

Abstract

This project involves simulating a toll booth system to analyze vehicle movements and toll payments using discrete-event simulation. The simulation is implemented with SimPy, GeoPandas, and Geopy libraries to provide a comprehensive analysis and visualization of vehicle behaviors in relation to toll booth interactions.

The toll booth is geographically located at a specific coordinate, and a predefined toll amount is set for vehicles within a 50 km radius. The project simulates three types of vehicles—Truck, Car, and Bus—each starting from different locations with initial account balances. The simulation tracks their movements, checks their proximity to the toll booth, and deducts the toll amount from their balances if applicable.

Key steps in the simulation include:

1. Defining the toll booth location and toll amount.
2. Initializing vehicle data with their types, locations, and account balances.
3. Creating a simulation environment and defining vehicle processes to simulate toll booth interactions.
4. Calculating distances from the toll booth and determining toll applicability.
5. Updating vehicle balances based on toll payments and simulating passage through the toll booth.
6. Visualizing the locations of the toll booth and vehicles using GeoPandas.

The results of the simulation demonstrate how vehicles with different starting locations and balances interact with the toll booth, providing insights into toll payment behaviors and financial implications. The visualization further aids in understanding the geographic aspects of the simulation, showcasing the spatial distribution of vehicles and the toll booth. This project highlights the practical application of simulation and geographic data analysis in managing and studying toll booth systems.

INTRODUCTION

The GPS-based Toll Collection System Simulation project provides a framework for simulating toll collection operations, integrating various Python libraries to create a dynamic environment. It aims to give students a practical understanding of toll collection systems through key concepts like vehicle movement, toll zone definitions, and payment processing.

The core components of the simulation include predefined routes marked by GPS coordinates, the identification of toll zones, distance calculations, toll charge computations, and payment processing. By utilizing SimPy for event-driven simulation, GeoPandas and shapely for geospatial analysis, GeoPy for distance calculations, pandas for data handling, and Matplotlib and Folium for visualization, the project combines data analytics and visualization techniques.

The project simulates vehicles such as cars, buses, and trucks moving through toll zones, calculating distances and determining charges based on predefined rates. These toll charges are deducted from simulated user accounts, mimicking real-world transactions. SimPy manages the event-driven simulation, while GeoPandas and shapely define toll zones and check intersections. GeoPy ensures precise distance calculations between GPS points. Data management and analysis are handled using pandas, with visualizations provided by Matplotlib and Folium.

The simulation workflow includes setting up the environment with a road network and toll zones using geospatial data, and initializing vehicles with starting points and destinations. As vehicles move, SimPy updates their GPS coordinates, and shapely and GeoPandas check for toll zone intersections. Charges are calculated based on travel distance or fixed fees for zone crossings and deducted from user accounts.

The project also generates reports on vehicle movements and toll collections, offering insights into the performance and dynamics of toll collection systems. The main challenges involve accurately simulating vehicle movements, optimizing performance for numerous transactions, and integrating diverse components for a cohesive operation.

The project also generates detailed reports on vehicle movements and toll collections, offering valuable insights into system performance and operational dynamics. Despite challenges in accuracy, optimization, and integration, it serves as a comprehensive educational tool for understanding toll collection systems.

LITERATURE REVIEW

The paper "Automated Toll Collection System using GPS and GPRS" by Sudheer Kumar Nagothu, presented at ICCSP 2016, proposes a system that uses GPS for vehicle location tracking and GPRS for communication. Vehicles equipped with GPS devices send their location data to a central server via GPRS as they approach toll gates. The server calculates the toll based on entry and exit points and deducts it from the vehicle owner's prepaid account. This system aims to reduce congestion, save time, and minimize human error in toll collection. [1].

The paper "Development of a GPS-based Highway Toll Collection System" by Jin Yeong Tan, Pin Jern Ker, Dineis Mani, and Puvanesan Arumugam, presented at the 2016 IEEE ICCSCE, describes the creation of a toll collection system using GPS technology. The system tracks vehicle locations via GPS and calculates tolls based on the distance traveled on the highway. Data is transmitted to a central server, which processes toll payments automatically. This approach aims to enhance efficiency, reduce traffic congestion, and streamline the toll collection process [2].

The paper "Estimation of System Delay Based Toll Equivalency Factors at Toll Plazas Using Simulation" by Chintaman S. Bari, Satish Chandra, and Ashish Dhamaniya, published in the International Journal of Transportation Science and Technology in 2023, investigates toll equivalency factors by simulating delays at toll plazas. It analyzes the impact of various delay factors on toll collection efficiency and proposes a methodology to quantify these delays. The study aims to optimize toll plaza operations by understanding and mitigating delay-related inefficiencies, thereby improving traffic flow and reducing waiting times for vehicles [3].

The paper "Traffic Simulation for Expressway Toll Plaza Based on Successive Vehicle Tracking Data" by Takahiro Shitama, Ryota Horiguchi, Hirokazu Akahane, and Jian Xing, presented at the 2006 International Symposium of Transport Simulation, explores a simulation model for expressway toll plazas using real-time vehicle tracking data. The study focuses on analyzing vehicle behavior and traffic flow at toll plazas to optimize operations. By tracking successive vehicle movements, the simulation aims to identify bottlenecks and improve toll plaza efficiency. The research provides insights into managing traffic congestion and enhancing the overall performance of toll collection systems [4].

The paper "Minimizing Toll Payment Queue using GPS-Based Mobile Applications" by Danang Dismantoro, Istas Pratomo, and Surya Sumpeno, presented at the 2020 Fifth International Conference on Informatics and

Computing (ICIC), discusses the development of a mobile application that utilizes GPS technology to minimize toll payment queues. The application allows drivers to pay tolls automatically as they approach toll plazas, reducing wait times and congestion. By integrating GPS for vehicle tracking and mobile payment systems, the solution aims to streamline the toll collection process and enhance the overall efficiency of toll plaza operations [5].

METHODOLOGY

1. Setup Environment

- This section sets up the geospatial data for the road network, toll zones, and vehicle locations:
- Define Road Network and Toll Zones Using Geospatial Coordinates
- You defined the toll booth location and vehicle starting points using geospatial coordinates.

2. Simulate Vehicle Movement

- Simulation Environment:
- Created a simulation environment using SimPy.
- Defined a vehicle function to simulate vehicle movements and toll payments.
- Vehicles are simulated to arrive at different times.

3. Detect Toll Zone Crossings

- The distance to the toll booth is calculated using the geodesic distance from the geopy library.
- Vehicles within a certain range (50 km) are subject to toll charges.

4. Calculate Toll Charges

- Toll charges are determined based on the distance to the toll booth.
- Vehicles pay the toll if their balance is sufficient.

5. Simulate Payments

- Toll charges are deducted from the vehicle's balance.
- The remaining balance or lack of funds is printed for each vehicle.

6. Analytics and Reporting

Visualization:

- Geospatial data for vehicle routes and toll booth location are plotted using GeoPandas and Matplotlib.
- Different colours are used for each vehicle's route for clarity

Results and Discussion

Results

The simulation was conducted using SimPy, GeoPandas, and Geopy to model the interactions between various vehicles and a toll booth system. The key results are summarized below:

1. Distance Calculation and Toll Applicability:

- Distances from each vehicle's starting location to the toll booth were calculated using the geodesic method from Geopy.
- Vehicles within a 50 km radius of the toll booth were required to pay the toll amount.

2. Toll Payment and Balance Update:

- Vehicles with sufficient balance at the time of passing the toll booth successfully paid the toll, and their remaining balances were updated accordingly.
- Vehicles without sufficient balance could not pay the toll, which was indicated in the simulation logs.

3. Simulation Logs:

- Detailed logs provided information on each vehicle's initial balance, distance to the toll booth, toll amount incurred, and remaining balance after the toll payment.
- Logs also recorded the passage of vehicles through the toll booth, marking whether the toll was successfully paid.

4. Geospatial Visualization:

- A Geodata Frame was created to visualize the geographic locations of the toll booth and the vehicles.
- The visualization displayed the spatial distribution of the vehicles in relation to the toll booth, highlighting the vehicles within the toll-

applicable range.

Discussion

The results of the simulation provide several insights into the toll booth system and its interaction with different vehicles:

1. Toll Collection Efficiency:

- The simulation demonstrated the system's efficiency in identifying vehicles within the toll-applicable range and processing toll payments based on their account balances.
- This efficiency can be leveraged to optimize real-world toll collection processes by understanding vehicle movement patterns and financial readiness for toll payments.

2. Financial Management:

- The simulation highlighted the importance of maintaining sufficient balances in vehicle accounts to ensure uninterrupted transit through toll booths.
- Transport companies can use such simulations to better manage their financial planning, ensuring that their fleet is adequately funded to avoid delays and penalties.

3. Geospatial Analysis:

- The geospatial visualization provided a clear representation of vehicle positions and their interactions with the toll booth.
- This analysis is crucial for planning toll booth placements, understanding traffic flow, and identifying high-traffic areas where toll booths could be strategically placed to maximize revenue.

4. Simulation Utility:

- The use of SimPy for discrete-event simulation proved effective in modeling real-world scenarios involving multiple entities and events.
- The integration of GeoPandas and Geopy for geographic data handling and distance calculation added depth to the simulation, making it a robust tool for transport and logistics analysis.

Conclusion

The GPS toll-based system simulation using Python demonstrates several significant advantages:

- 1. Efficiency and Automation:** The system automates toll collection, eliminating the need for physical toll booths. Vehicles are charged based on their GPS-tracked routes, which significantly reduces traffic congestion typically caused by manual toll collection processes.
- 2. Accuracy:** GPS technology allows for precise location tracking. This accuracy ensures that drivers are charged appropriately based on the actual distance they travel, promoting fairness and reducing discrepancies in toll collection.
- 3. User Convenience:** Drivers benefit from a seamless experience, as they do not need to stop at toll booths. This not only saves time but also enhances the overall travel experience.
- 4. Cost Reduction:** The reduction in physical infrastructure and personnel requirements leads to lower operational costs. Maintenance costs for toll booths are also eliminated.
- 5. Scalability:** The simulation, built using Python, demonstrates that the system can be scaled to accommodate various road networks and tolling schemes. This adaptability makes it suitable for different geographical regions and traffic conditions.
- 6. Environmental Benefits:** By reducing the need for vehicles to stop and start at toll booths, the system can lead to smoother traffic flow, decreased fuel consumption, and lower vehicle emissions, contributing to a reduction in the overall environmental footprint of road transport.

In summary, the project showcases the potential of integrating GPS technology with toll collection systems to create a more efficient, user-friendly, and cost-effective solution

Future Scope

Several areas can be explored to further enhance the GPS toll-based system:

- 1. Real-Time Data Integration:** Integrating real-time traffic data can optimize toll rates based on current traffic conditions. For example, dynamic pricing could be implemented, where toll rates vary depending on traffic congestion levels, encouraging off-peak travel and reducing congestion.
- 2. Security Enhancements:** To ensure the integrity of the system, robust security measures must be implemented. This includes protections against GPS spoofing, encryption of data transmissions, and secure storage of user information.
- 3. Integration with Payment Systems:** Seamless integration with various digital payment platforms (e.g., mobile wallets, credit/debit cards, bank transfers) can enhance user convenience. Automated billing and notifications can be implemented to keep users informed of their charges.
- 4. Vehicle Classification:** The system can be improved to automatically classify different types of vehicles (e.g., cars, trucks, motorcycles) using machine learning or sensor data. Different toll rates can then be applied based on the vehicle type, reflecting the wear and tear caused by different vehicles.
- 5. Multi-Lane and Multi-Road Support:** Extending the simulation to support complex road networks, including highways, urban roads, and rural roads, can make the system more versatile. This involves handling multiple lanes, varying speed limits, and different types of toll roads.
- 6. User Feedback and Optimization:** Implementing a feedback mechanism allows users to report issues and suggest improvements. Continuous monitoring and analysis of system performance can help in making iterative enhancements, ensuring the system remains efficient and user-friendly.

7. Policy and Regulatory Compliance: The system must comply with local and international regulations regarding toll collection, data privacy, and transportation. This includes adhering to standards set by transportation authorities and ensuring user data is handled responsibly.

8. Environmental Impact Analysis: Assessing the environmental benefits of the system can provide valuable insights. This includes analyzing fuel savings and reduced emissions due to decreased idling times at toll booths and smoother traffic flow. These insights can be used to promote the system as an environmentally friendly alternative.

By addressing these future scope areas, the GPS toll-based system can evolve into a comprehensive, robust, and widely adopted solution for modern toll collection. This will not only improve efficiency and user experience but also contribute to better traffic management and environmental sustainability.

Materials and resources

<https://github.com/himarg22/gpstollsystem.git>

Reference

1. Nagothu, S.K., 2016, April. Automated toll collection system using GPS and GPRS. In *2016 International Conference on Communication and Signal Processing (ICCSP)* (pp. 0651-0653). IEEE.
2. Tan, J.Y., Ker, P.J., Mani, D. and Arumugam, P., 2016, November. Development of a GPS-based highway toll collection system. In *2016 6th IEEE International Conference on Control System, Computing and Engineering (ICCSCE)* (pp. 125-128). IEEE.
3. Bari, C.S., Chandra, S. and Dhamaniya, A., 2023. Estimation of system delay-based toll equivalency factors at toll plazas using simulation. *International Journal of Transportation Science and Technology*, 12(3), pp.822-835.
4. Shitama, T., Horiguchi, R., Akahane, H. and Xing, J., 2006, July. Traffic simulation for expressway toll plaza based on successive vehicle tracking data. In *Proceeding of international symposium of transport simulation* (pp. 1-21).
5. Dismantoro, D., Pratomo, I. and Sumpeno, S., 2020, November. Minimizing Toll Payment Queue using GPS-Based Mobile

Appendix

```
import simpy
import geopandas as gpd
from geopy.distance import geodesic
from shapely.geometry import Point, LineString
import matplotlib.pyplot as plt

# Define the new toll booth location
toll_booth_location = (9.4981, 76.3388) # Alappuzha, Kerala

# Define vehicle locations with (latitude, longitude), initial account
balances, base toll amounts, and names
vehicle_data = [
    {'type': 'Truck', 'name': 'Kottayam', 'location': (9.5916, 76.5221),
    'balance': 10000.0, 'destination': (9.9312, 76.2673), 'base_toll': 20.0,
    'start_time': 6 * 60},
    {'type': 'Car', 'name': 'Changanassery', 'location': (9.4420, 76.5363),
    'balance': 5000.0, 'destination': (9.9833, 76.6150), 'base_toll': 5.0,
    'start_time': 11 * 60},
    {'type': 'Bus', 'name': 'Puthupally', 'location': (9.5674, 76.6310),
    'balance': 7500.0, 'destination': (9.9815, 76.5735), 'base_toll': 10.0,
    'start_time': 8 * 60}
]

# Define a GeoDataFrame for vehicle starting points, toll booth, and
destinations
gdf_points = gpd.GeoDataFrame(
    {
        'id': ['Toll Booth', 'Truck Start', 'Car Start', 'Bus Start', 'Truck
End', 'Car End', 'Bus End'],
        'geometry': gpd.points_from_xy(
            [toll_booth_location[1], vehicle_data[0]['location'][1],
            vehicle_data[1]['location'][1], vehicle_data[2]['location'][1],
            vehicle_data[0] ['destination'][1], vehicle_data[1]
['destination'][1], vehicle_data[2] ['destination'][1]],
            [toll_booth_location[0], vehicle_data[0]['location'][0],
            vehicle_data[1]['location'][0], vehicle_data[2]['location'][0],
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```

        vehicle_data[0] ['destination'][0], vehicle_data[1]
['destination'][0], vehicle_data[2] ['destination'][0]]

    )

}

)

# Define a GeoDataFrame for routes from vehicles to the toll booth and to
their destinations

gdf_routes = gpd.GeoDataFrame(

    {

        'id': ['Truck Route', 'Car Route', 'Bus Route'],

        'geometry': [

            LineString([Point(vehicle_data[0] ['location'][1],
vehicle_data[0] ['location'][0]), Point(toll_booth_location[1],
toll_booth_location[0]),

                        Point(vehicle_data[0] ['destination'][1],
vehicle_data[0] ['destination'][0]))),

            LineString([Point(vehicle_data[1] ['location'][1],
vehicle_data[1] ['location'][0]), Point(toll_booth_location[1],
toll_booth_location[0]),

                        Point(vehicle_data[1] ['destination'][1],
vehicle_data[1] ['destination'][0]))),

            LineString([Point(vehicle_data[2] ['location'][1],
vehicle_data[2] ['location'][0]), Point(toll_booth_location[1],
toll_booth_location[0]),

                        Point(vehicle_data[2] ['destination'][1],
vehicle_data[2] ['destination'][0]))

        ]

    }

)

# Define congestion level that affects toll prices

congestion_level = 1.5 # 1.0 = normal, > 1.0 = high congestion, < 1.0 = low
congestion

# Define dynamic toll pricing based on time of day and congestion

def get_dynamic_toll(base_toll, vehicle_type, time_of_day,
congestion_level):

    # Peak hours are 8-10 AM and 5-7 PM

    if 8 <= time_of_day < 10 or 17 <= time_of_day < 19:

        peak_factor = 1.5

    else:

        peak_factor = 1.0

```

```

# Different toll rates for different vehicle types
vehicle_factor = 1.0
if vehicle_type == 'Truck':
    vehicle_factor = 2.0
elif vehicle_type == 'Bus':
    vehicle_factor = 1.5

toll = base_toll * peak_factor * vehicle_factor * congestion_level

# Increase toll by additional percentages during specific time intervals
if 6.5 <= time_of_day < 7.5:
    toll *= 1.05
    print(f"Additional 5% toll applied for {vehicle_type} at
{time_of_day:.2f} hours.")
elif 8.5 <= time_of_day < 9.5:
    toll *= 1.08
    print(f"Additional 8% toll applied for {vehicle_type} at
{time_of_day:.2f} hours.")
elif 11.5 <= time_of_day < 12.5:
    toll *= 1.10
    print(f"Additional 10% toll applied for {vehicle_type} at
{time_of_day:.2f} hours.")

return toll

# Define a function to convert time in hours to HH:MM format
def convert_to_hhmm(hours):
    hh = int(hours)
    mm = int ((hours - hh) * 60)
    return f"{hh:02}: {mm:02}"

# Define a function to simulate vehicles passing through a toll
def vehicle (env, vehicle_id, data):
    vehicle_type = data['type']
    name = data['name']
    location = data['location']
    balance = data['balance']
    base_toll = data['base_toll']

```

```

destination = data['destination']
start_time = data['start_time']

yield env.timeout(start_time) # Start the journey at the specified time
start_time_hr = env.now / 60 # Convert start time to hours

print(f"Time: {convert_to_hhmm(start_time_hr)} - {vehicle_type} from
{name} ({location}) starts the journey with a balance of {balance:.2f}.")

# Simulate arrival time based on distance and an average speed of 50
km/h
distance_to_toll = geodesic(location, toll_booth_location).km
travel_time = distance_to_toll / 50 * 60 # convert hours to minutes
yield env.timeout(travel_time)

time_of_day = (env.now / 60) % 24 # Get the current time in hours
total_toll = get_dynamic_toll(base_toll, vehicle_type, time_of_day,
congestion_level)

if balance >= total_toll:
    balance -= total_toll
    print(f"Time: {convert_to_hhmm(env.now / 60)} - {vehicle_type} from
{name} ({location}) reached the toll booth, incurred a toll of
{total_toll:.2f}, and has a remaining balance of {balance:.2f}.")
else:
    print(f"Time: {convert_to_hhmm(env.now / 60)} - {vehicle_type} from
{name} ({location}) reached the toll booth but does not have enough balance
to pay the toll.")

# Simulate remaining travel to destination
distance_to_destination = geodesic(toll_booth_location, destination).km
travel_time_to_destination = distance_to_destination / 50 * 60
yield env.timeout(travel_time_to_destination)
end_time_hr = env.now / 60 # Convert end time to hours

print(f"Time: {convert_to_hhmm(end_time_hr)} - {vehicle_type} has
reached its destination at {destination}.")

# Define a simulation environment
env = simpy.Environment()

# Create processes for each vehicle
for i, data in enumerate(vehicle_data, start=1):

```

```

env.process(vehicle(env, i, data))

# Run the simulation

env.run()

# Plot the locations and routes on a map with different colors for each
vehicle's route

fig, ax = plt.subplots(1, 1, figsize=(10, 10))

gdf_points.plot(ax=ax, color='blue', marker='o', markersize=50,
label='Locations')

gdf_routes[gdf_routes['id'] == 'Truck Route'].plot(ax=ax, color='orange',
linewidth=2, label='Truck Route')

gdf_routes[gdf_routes['id'] == 'Car Route'].plot(ax=ax, color='green',
linewidth=2, label='Car Route')

gdf_routes[gdf_routes['id'] == 'Bus Route'].plot(ax=ax, color='purple',
linewidth=2, label='Bus Route')

# Annotate the points with vehicle type and names

for x, y, label in zip(gdf_points.geometry.x, gdf_points.geometry.y,
gdf_points.id):

    ax.text(x, y, label, fontsize=12, ha='right')

plt.title("Vehicle Routes and Toll Booth in Kerala")

plt.legend()

plt.show()

```

Output

Time: 06:00 - Truck from Kottayam ((9.5916, 76.5221)) starts the journey with a balance of 10000.00.

Time: 06:27 - Truck from Kottayam ((9.5916, 76.5221)) reached the toll booth, incurred a toll of 60.00, and has a remaining balance of 9940.00.

Time: 07:25 - Truck has reached its destination at (9.9312, 76.2673).

Time: 08:00 - Bus from Puthupally ((9.5674, 76.631)) starts the journey with a balance of 7500.00.

Additional 8% toll applied for Bus at 8.66 hours.

Time: 08:39 - Bus from Puthupally ((9.5674, 76.631)) reached the toll booth, incurred a toll of 36.45, and has a remaining balance of 7463.55.

Time: 09:50 - Bus has reached its destination at (9.9815, 76.5735).

Time: 11:00 - Car from Changanassery ((9.442, 76.5363)) starts the journey with a balance of 5000.00.

Time: 11:27 - Car from Changanassery ((9.442, 76.5363)) reached the toll booth, incurred a toll of 7.50, and has a remaining balance of 4992.50.

Time: 12:41 - Car has reached its destination at (9.9833, 76.615).



