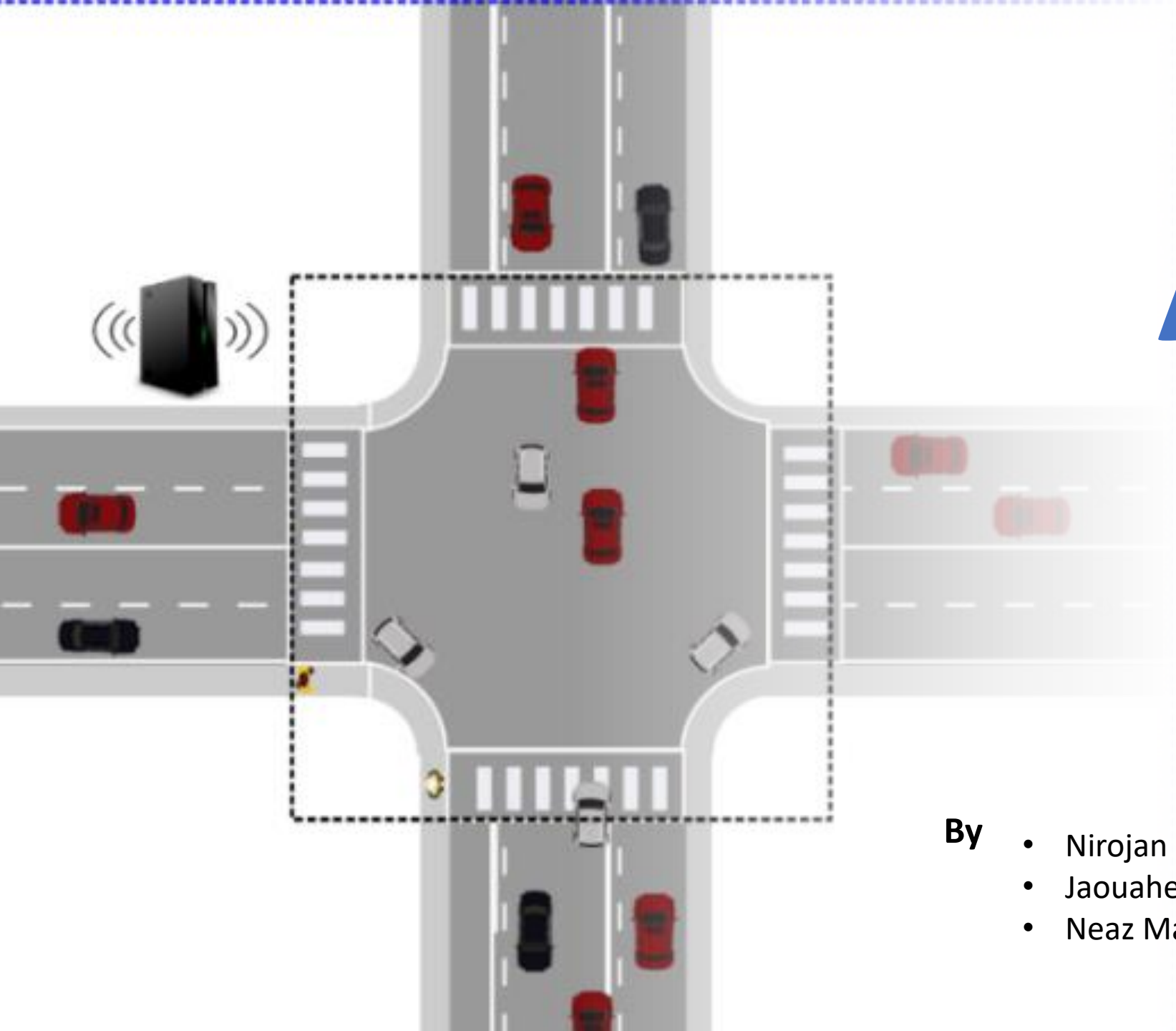


Autonomous Intersection Controller

By

- Nirojan Navaratanarajah
- Jaouaher Belgacem
- Neaz Mahmud

MOTIVATION

Problematic

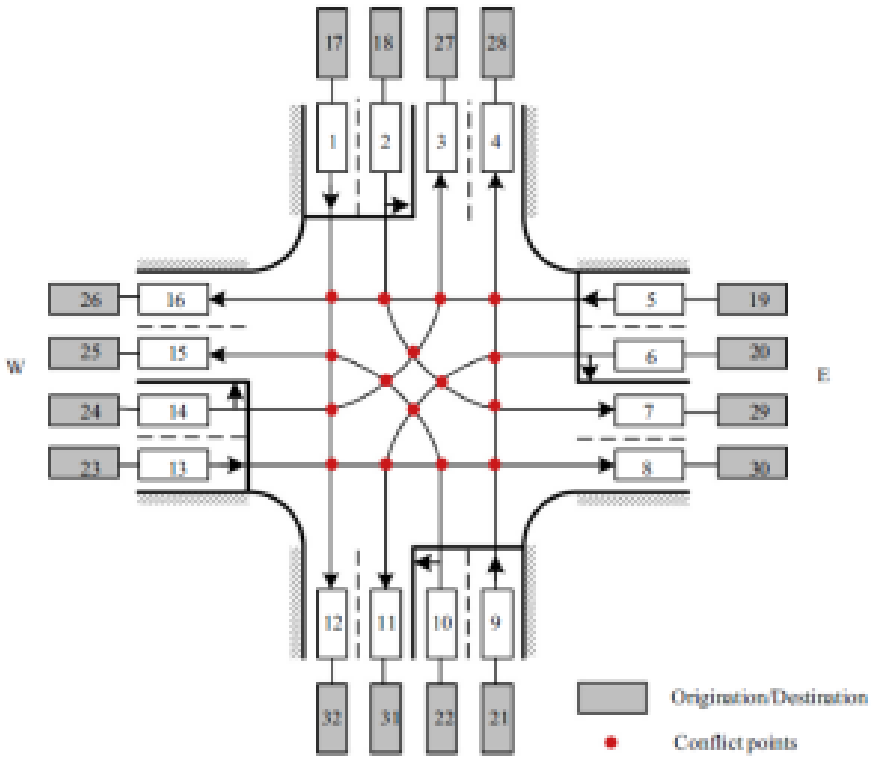
- **Entry/Destination possibilities**

Entry North:
- South
- East
- West

Entry South:
- North
- East
- West

Entry West:
- South
- North
- East

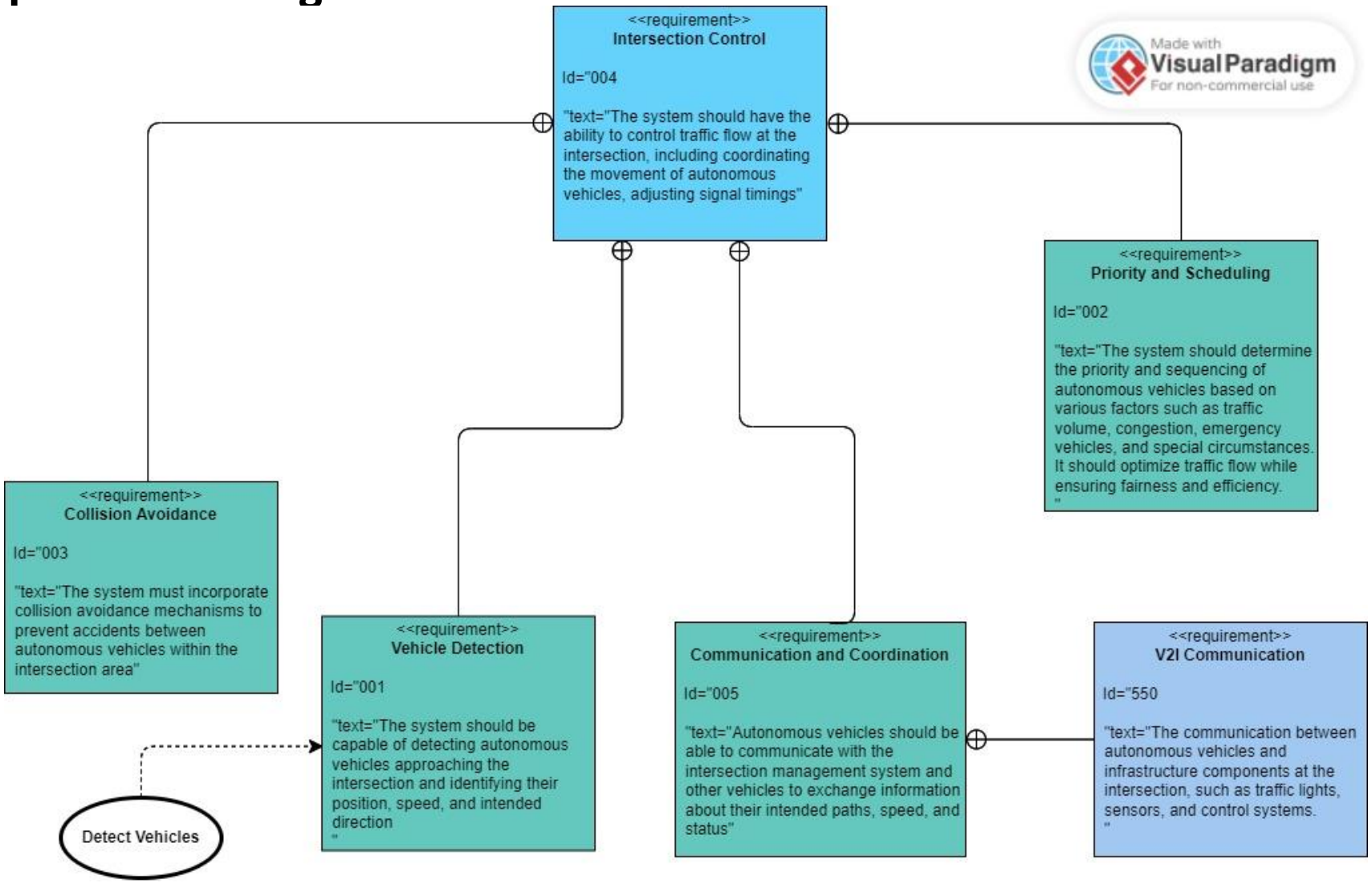
Entry East:
- South
- North
- West



[1]

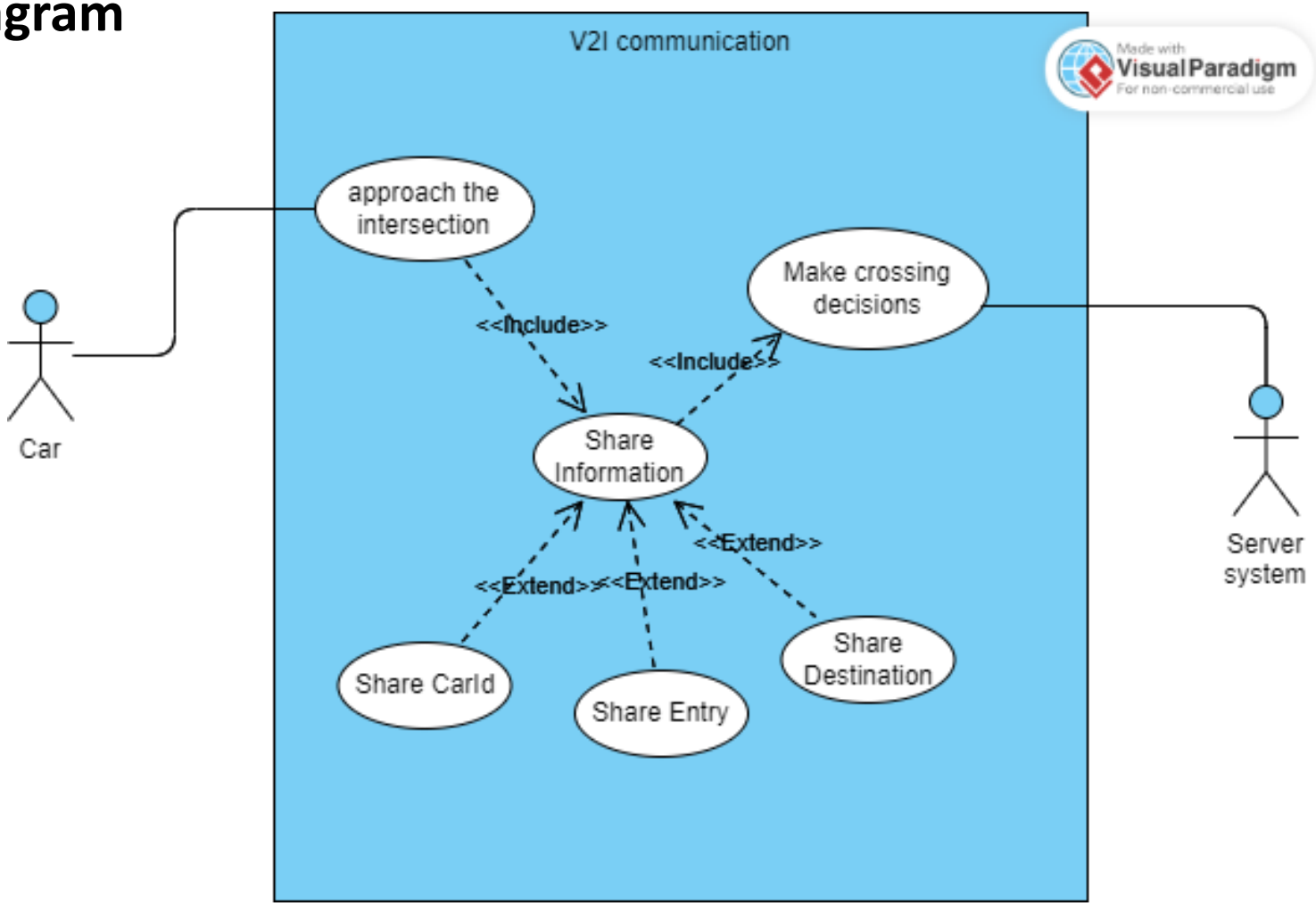
Software Modelling

- **Requirement Diagram**



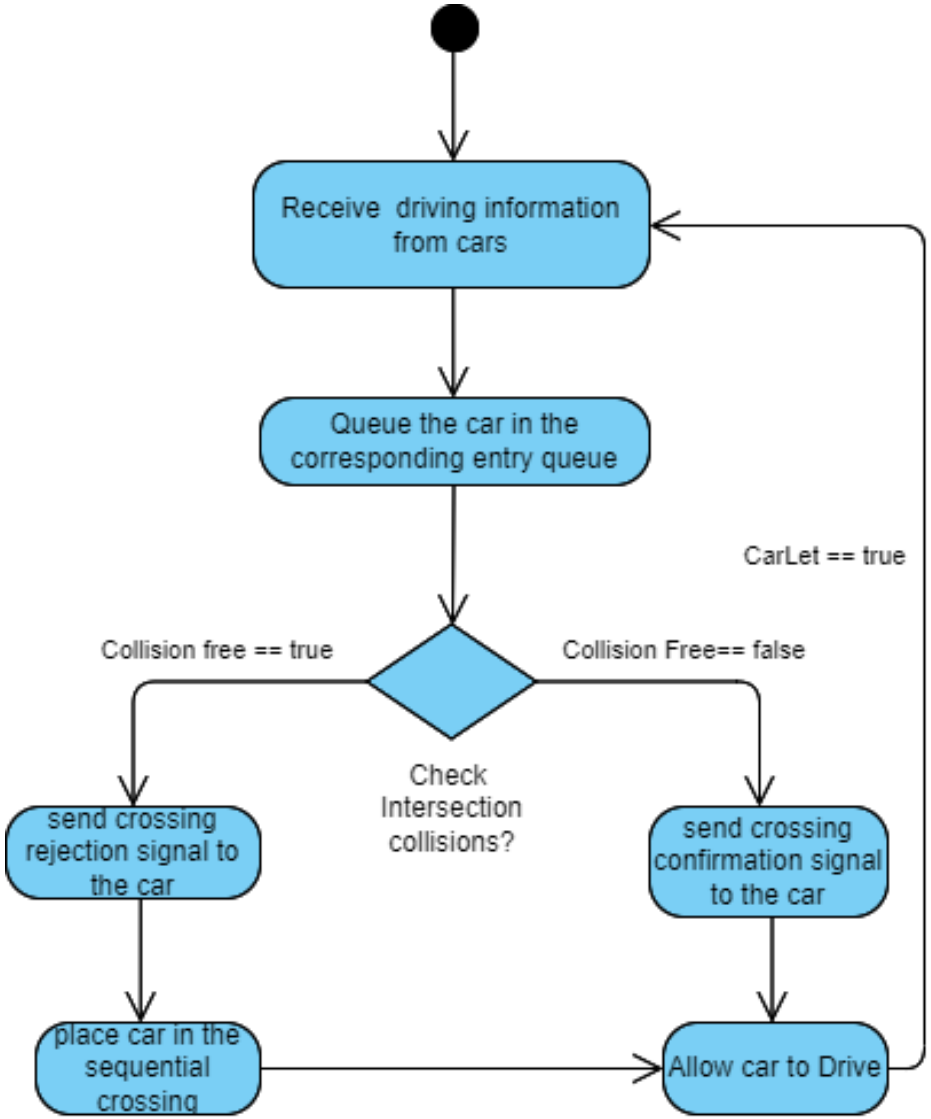
Software Modelling

- **Use Case Diagram**



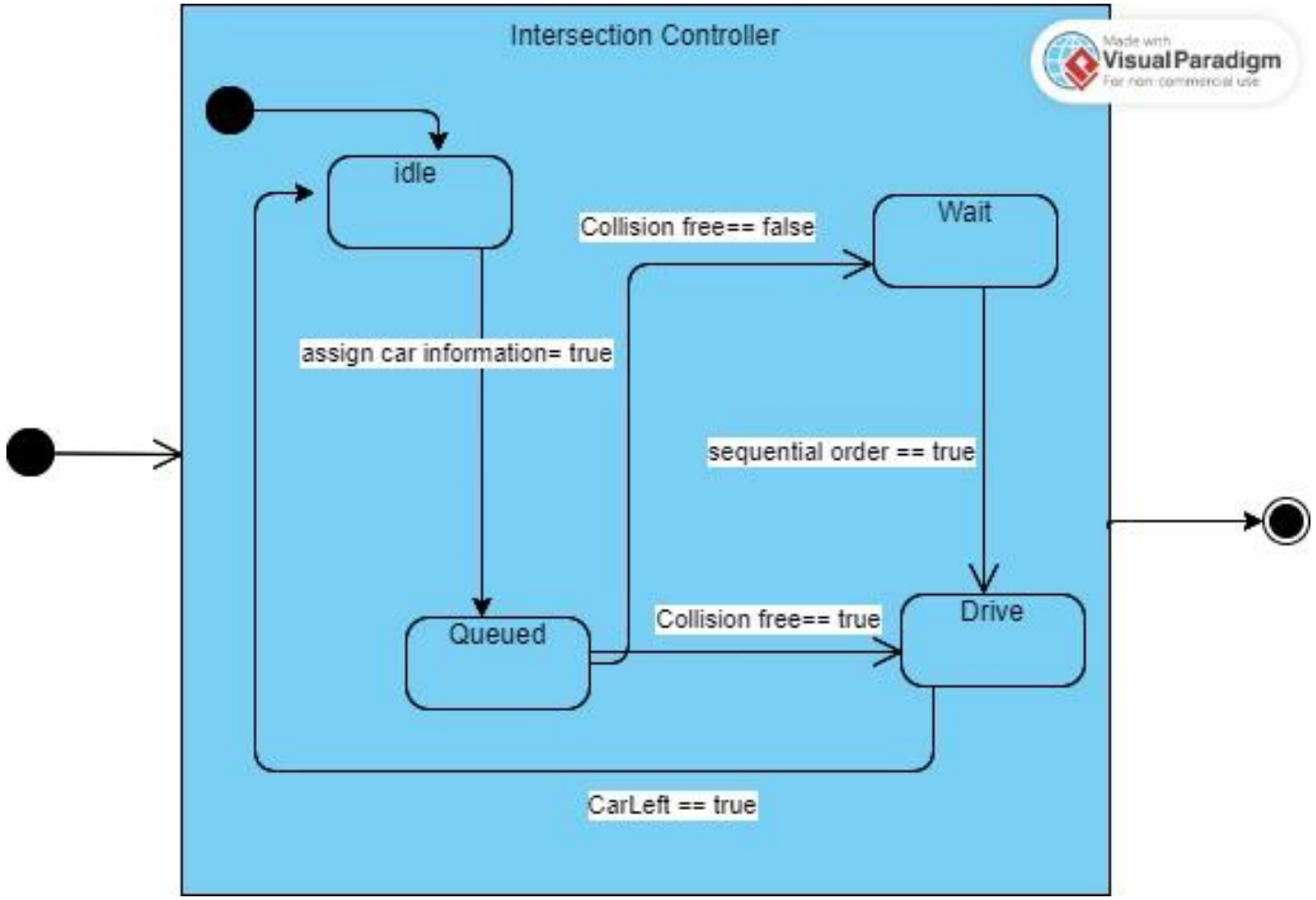
Software Modelling

- **Activity Diagram**



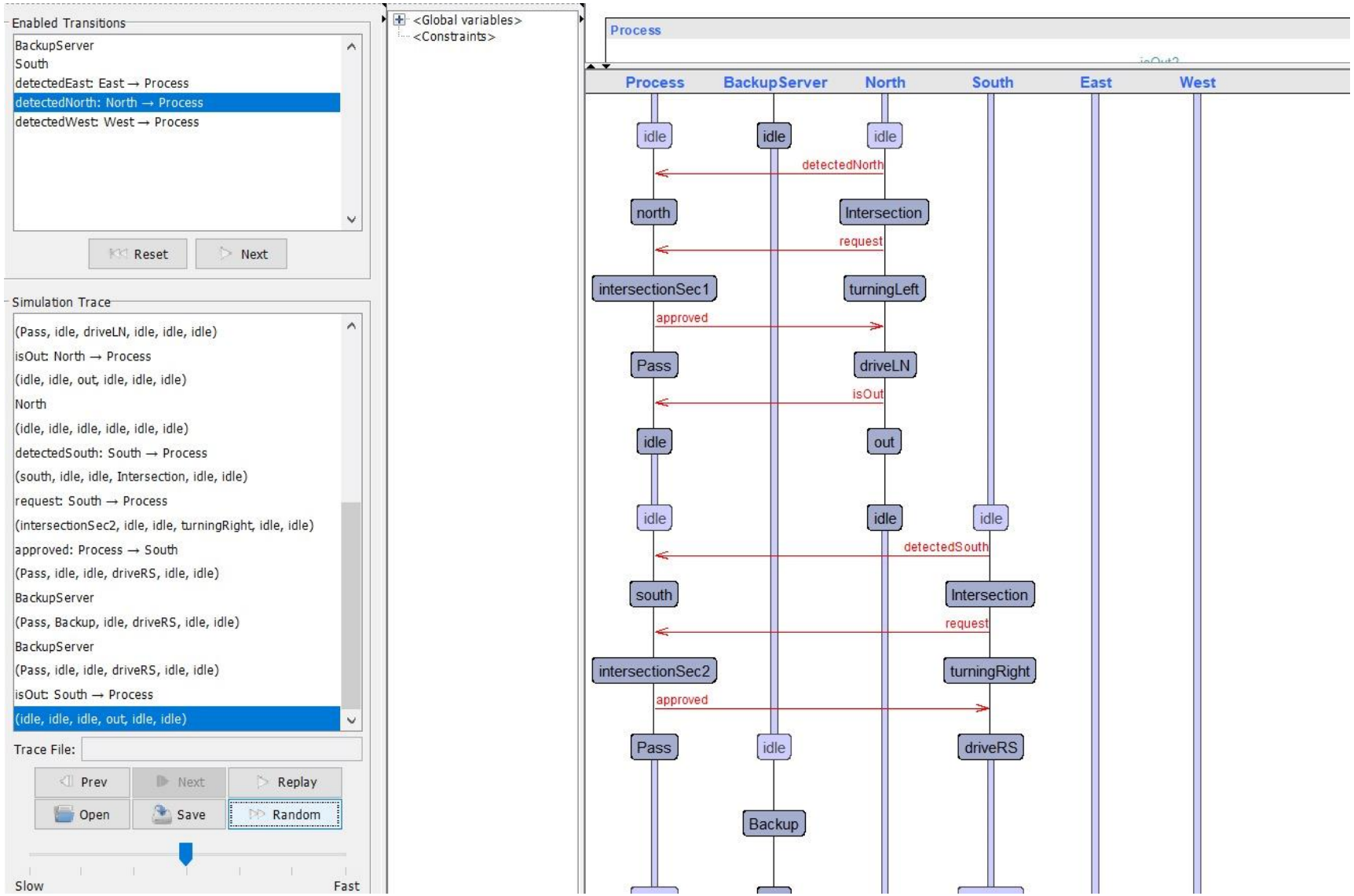
Software Modelling

- **State Machine Diagram**



Upaal Implementation

- **System's simulation**



Uppaal Implementation

- **System's verification**

Overview

```
A[]!deadlock
E<>North.out
```

Query

```
E<>North.out
```

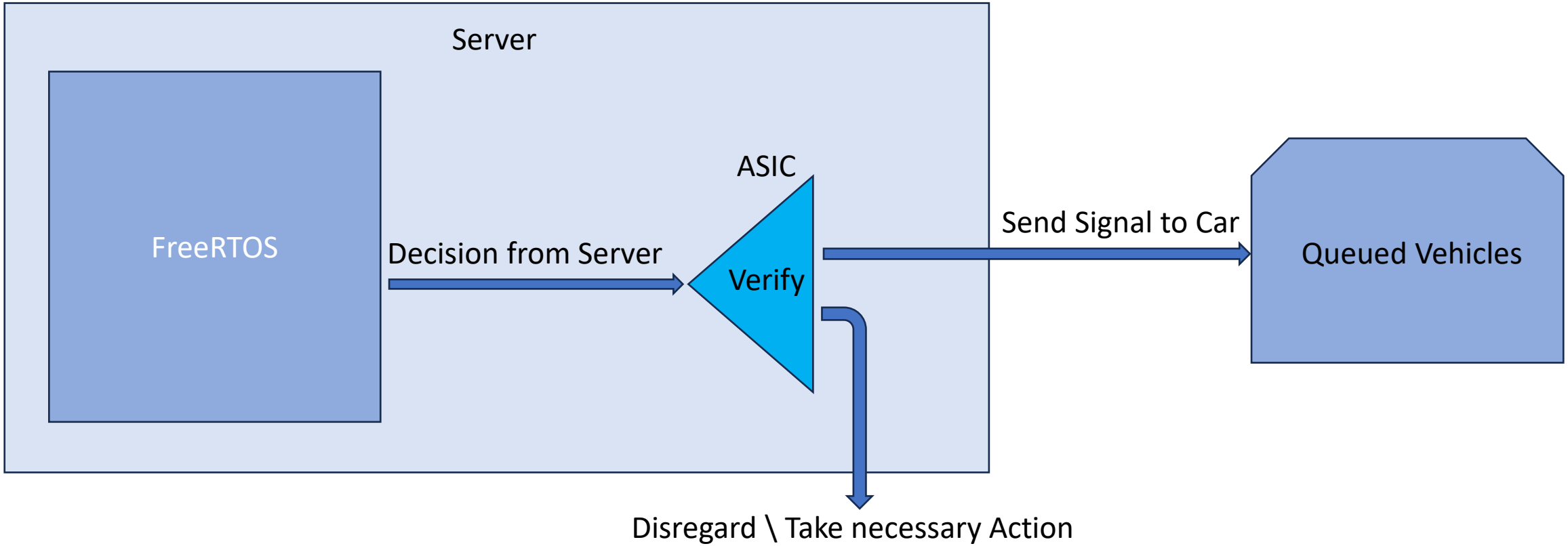
Comment

Status

```
E<>North.out
Verification/kernel/elapsed time used: 0s / 0s / 0.007s.
Resident/virtual memory usage peaks: 10,760KB / 49,672KB.
Property is satisfied.
```

Hw/Sw Codesign Implementation

- **ASIC design**



Hw/Sw Codesign Implementation

- **VHDL Code snippets**

```
-- Scenario: Only cars coming from opposite directions can go straight at the same time
elsif (Car1 = '1' and Car2 = '1' and Car3 = '0' and Car4 = '0') then
    Car1Permission <= "111";
    Car2Permission <= "111";
    Car3Permission <= "000";
    Car4Permission <= "000";
    Collision <= '0';
```

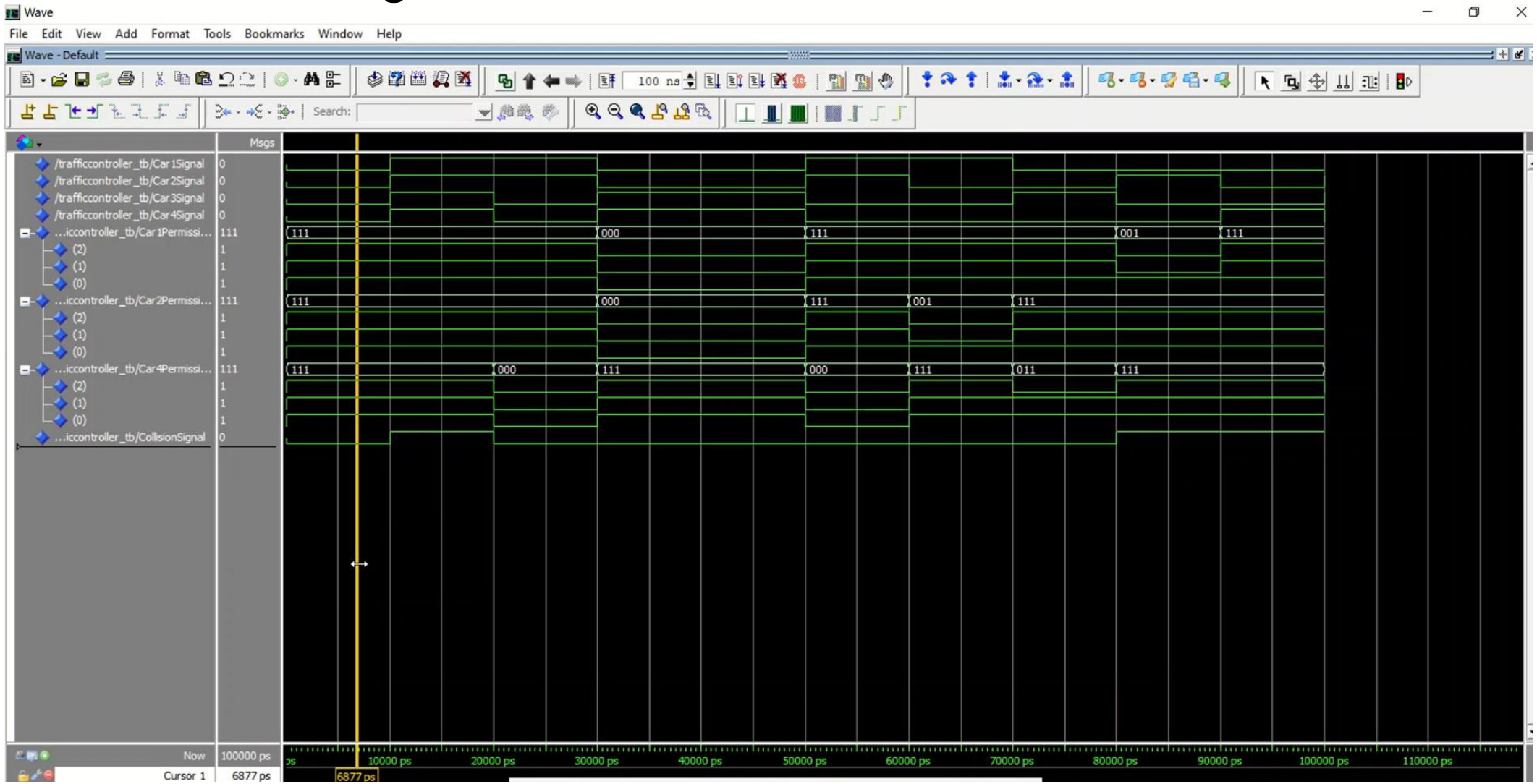
```
elsif (Car1 = '0' and Car2 = '1' and Car3 = '1' and Car4 = '0') then
    Car1Permission <= "001";
    Car2Permission <= "111";
    Car3Permission <= "111";
    Car4Permission <= "111";
    Collision <= '1';
```

```
-- Car 2 goes right, Car 4 goes right
Car1Signal <= '0';
Car2Signal <= '1';
Car3Signal <= '0';
Car4Signal <= '1';

wait for 10 ns;
```

```
-- Car 1 goes left, Car 2 goes right,
-- Car 3 goes straight, Car 4 goes right
Car1Signal <= '0';
Car2Signal <= '1';
Car3Signal <= '1';
Car4Signal <= '1';
```

Hw/Sw Codesign Implementation

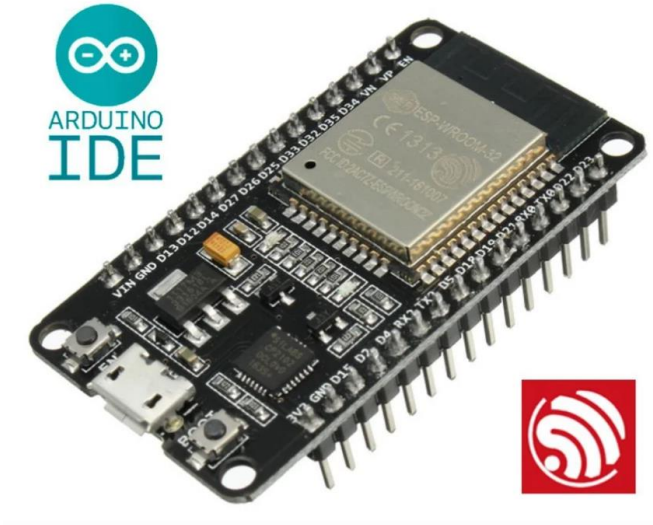
- **VHDL Simulation using Modelsim**



FreeRTOS Implementation

- **Solution approach**

+



[2]

[3]

FreeRTOS Implemetations

- **Why ESP-IDF?**

Advantages

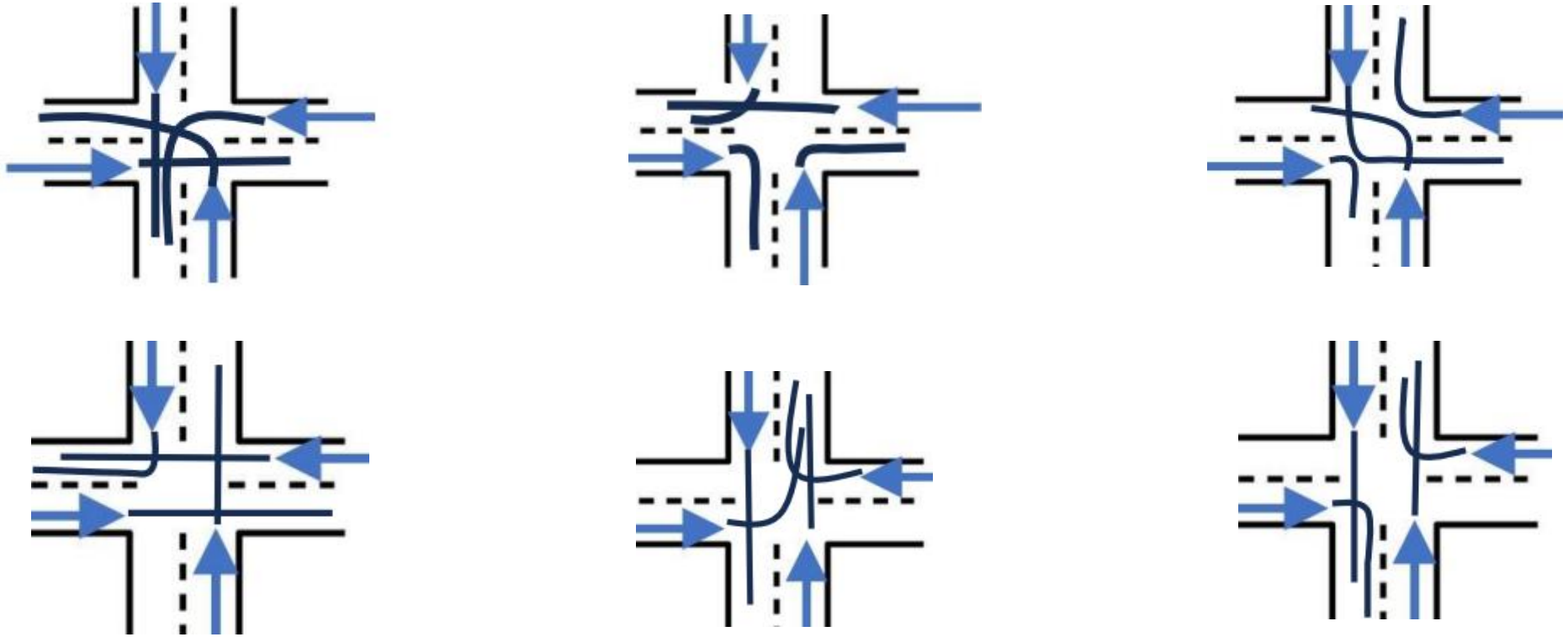
- Enhanced Functionality (library, tools, APIs)
- Access to Advanced Features (Wi-Fi, Bluetooth)
- Rich Documentation and Community Support

Drawbacks

- Complexity and Development Time
- Hardware-Specific (Espressif's ESP32 and ESP8266

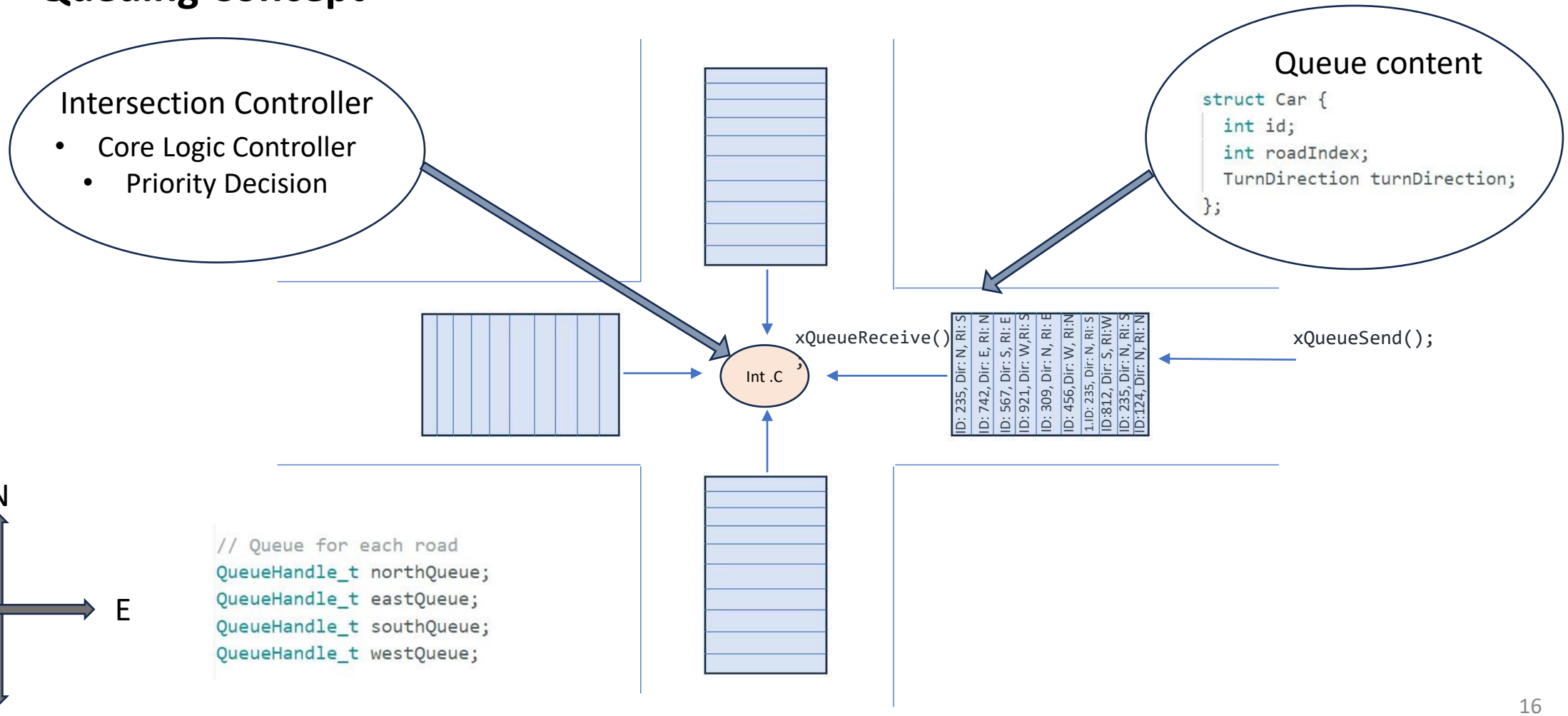
FreeRTOS Implemetations

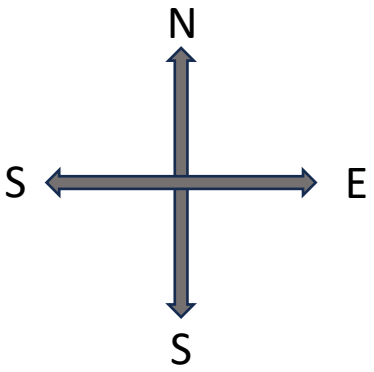
- **Problematic Scenarios**



FreeRTOS Implemetations

- **Queuing Concept**





FreeRTOS Implemetations

- **Snippets of code**

Semaphores creation

```
carPassedMutex = xSemaphoreCreateMutex();
deadlockSemaphore = xSemaphoreCreateBinary();
```

Queues creation

```
// Create the queues for each road
northQueue = xQueueCreate(10, sizeof(Car));
eastQueue = xQueueCreate(10, sizeof(Car));
southQueue = xQueueCreate(10, sizeof(Car));
westQueue = xQueueCreate(10, sizeof(Car));
```

Tasks Creation

```
  // Create the intersection controller task
  xTaskCreatePinnedToCore(intersectionControllerTask, "IntersectionControllerTask", 4096, NULL, 1, NULL,tskNO_AFFINITY);
  xTaskCreatePinnedToCore(fillCarIdDirToQueues, "fillQueues", 4096, NULL, 1, NULL,tskNO_AFFINITY);
// Create the deadlock detection task and schedule it to run on Core 0
  xTaskCreatePinnedToCore(deadlockDetectionTask, "DeadlockDetectionTask", 4096, NULL, 1, NULL,tskNO_AFFINITY);
```

FreeRTOS Implemetations

- **Snippets of code**

Sending to the queue

```
// Cars approaching from the North road
if (uxQueueSpacesAvailable(northQueue) > 0) {
  Car northCar;
  northCar.id = random(1000);
  northCar.roadIndex = 0; // North road index
  northCar.turnDirection = static_cast<TurnDirection>(random(1, 4));
  xQueueSend(northQueue, &northCar, portMAX_DELAY);
```

Binary Semaphore

```
xSemaphoreTake(carPassedMutex, portMAX_DELAY);
carPassed = true;
xSemaphoreGive(carPassedMutex);
```

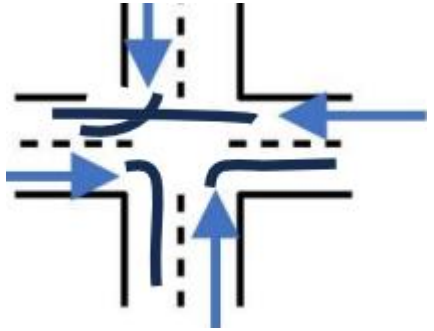
Reading from queue

```
void intersectionControllerTask(void* parameter) {
  int count = 0;

  while (true) {
    // Check the queues and allow cars to pass based on booking order
    Car car;

    if (xQueueReceive(northQueue, &car, 0) == pdTRUE) {
      // Check for a matching scenario with a car approaching from the South road
      Car oppositeCar;
      if (xQueueReceive(southQueue, &oppositeCar, 0) == pdTRUE && car.turnDirection == oppositeCar.turnDirection)
```

FreeRTOS Implemetations

- **Results**

```
Car ID: 432, Approaching from:--> North road, Wants to turn:---> Right
Car ID: 773, Approaching from:--> East road, Wants to turn:---> Straight
Car ID: 756, Approaching from:--> South road, Wants to turn:---> Right
Car ID: 940, Approaching from:--> West road, Wants to turn:---> Right
```



```
1. Car ID: 432 and 756 are both allowed to pass simultaneously (Both going Straight / turning right).
-------------------------------------------------------------------------------------------------------------------------------

   Normal Sequence : North_Car is allowed to cross the junction -> East_Car,-> Southast_Car,-> West_Car in sequence.
```

FreeRTOS Implemetations

- **Running FreeRTOS on Hardware**

File Edit Sketch Tools Help

ESP32 Wrover Module

car_1.ino

```
#include <Arduino.h>
#include <freertos/FreeRTOS.h>
#include <freertos/task.h>
#include <freertos/queue.h>
#include <freertos/semphr.h>

// Define the turn direction options
enum TurnDirection {
  LEFT,
  STRAIGHT,
  RIGHT
};

// Define the road names
const char* roadNames[] = {"North", "East", "South", "West"};
SemaphoreHandle_t deadlockSemaphore;
SemaphoreHandle_t carPassedMutex;

// Structure to represent a car
struct Car {
  int id;
  int roadIndex;
  TurnDirection turnDirection;
};

// Queue for each road
QueueHandle_t northQueue;
QueueHandle_t eastQueue;
QueueHandle_t southQueue;
QueueHandle_t westQueue;

// Flag to track if a car has been allowed to pass
bool carPassed = false;
```

Output Serial Monitor

Sketch uses 269982 bytes (20%) of program storage space. Maximum is 1310720 bytes.

00:00:16 00:01:42

Wiedergabe (STRG+P) Ln 282, Col 42 ESP32 Wrover Module on COM3

Conclusion

Questions ?

References

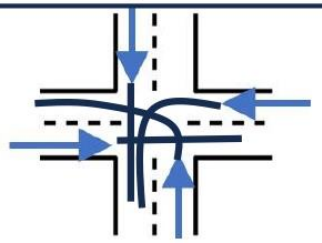
[1] S. V. U. Feng Zhu, “A linear programming formulation for autonomous intersection control within a dynamic traffic assignment and connected vehicle environment,” Transportation Research Part C, no. 55, p. 363–378, 2015

[2] https://www.freertos.org/index.html

[3] https://www.instructables.com/Installing-the-ESP32-Board-in-Arduino-IDE-Windows-/

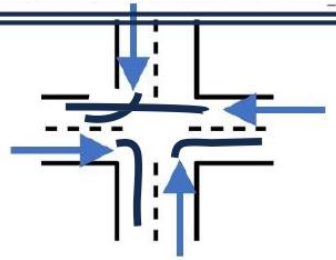
Different Scenarios on Serial Outputs 01

1



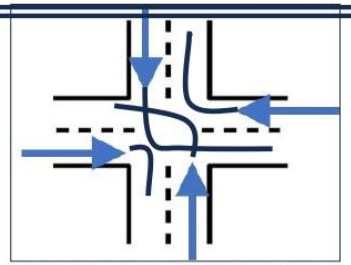
```
Car ID: 569, Approaching from:--> North road, Wants to turn:---> Straight
Car ID: 700, Approaching from:--> East road, Wants to turn:---> Left
Car ID: 879, Approaching from:--> South road, Wants to turn:---> Left
Car ID: 336, Approaching from:--> West road, Wants to turn:---> Straight

                    Normal Sequence : North_Car is allowed to cross the junction -> East_Car,-> Southast_Car,-> West_Car in sequence.
-------------------------------------------------------------------------------------------------------------------------------------

                    Normal Sequence : North_Car is allowed to cross the junction -> East_Car,-> Southast_Car,-> West_Car in sequence.
-------------------------------------------------------------------------------------------------------------------------------------
```

2



```
Car ID: 432, Approaching from:--> North road, Wants to turn:---> Right
Car ID: 773, Approaching from:--> East road, Wants to turn:---> Straight
Car ID: 756, Approaching from:--> South road, Wants to turn:---> Right
Car ID: 940, Approaching from:--> West road, Wants to turn:---> Right
                    1. Car ID: 432 and 756 are both allowed to pass simultaneously (Both going Straight / turning right).
-------------------------------------------------------------------------------------------------------------------------------------

                    Normal Sequence : North_Car is allowed to cross the junction -> East_Car,-> Southast_Car,-> West_Car in sequence.
-------------------------------------------------------------------------------------------------------------------------------------
```

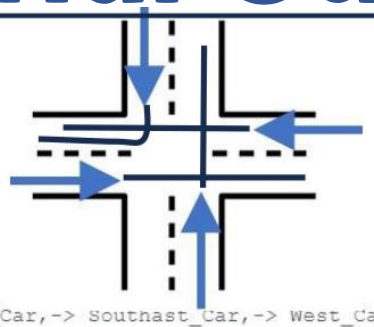
3



```
Car ID: 641, Approaching from:--> North road, Wants to turn:--->
Car ID: 432, Approaching from:--> East road, Wants to turn:---> Right
Car ID: 412, Approaching from:--> South road, Wants to turn:---> Left
Car ID: 148, Approaching from:--> West road, Wants to turn:---> Right

                    Normal Sequence : North_Car is allowed to cross the junction -> East_Car,-> Southast_Car,-> West_Car in sequence.
-------------------------------------------------------------------------------------------------------------------------------------
                    Car ID: 432 and 148 are both allowed to pass simultaneously (Both going Straight / turning right).
-------------------------------------------------------------------------------------------------------------------------------------
```

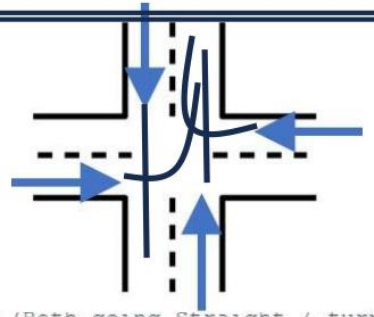
Different Scenarios on Serial Outputs 02

4



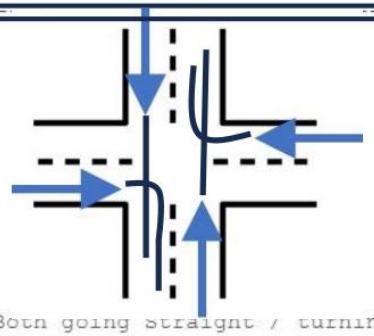
```
Car ID: 342, Approaching from:--> North road, Wants to turn:--->
Car ID: 22, Approaching from:--> East road, Wants to turn:---> Straight
Car ID: 410, Approaching from:--> South road, Wants to turn:---> Straight
Car ID: 739, Approaching from:--> West road, Wants to turn:---> Straight

                    Normal Sequence : North_Car is allowed to cross the junction -> East_Car,-> Southast_Car,-> West_Car in sequence.
-------------------------------------------------------------------------------------------------------------------------------------
                    Car ID: 22 and 739 are both allowed to pass simultaneously (Both going Straight / turning right).
-------------------------------------------------------------------------------------------------------------------------------------
```

5



```
Car ID: 958, Approaching from:--> North road, Wants to turn:---> Straight
Car ID: 488, Approaching from:--> East road, Wants to turn:---> Right
Car ID: 103, Approaching from:--> South road, Wants to turn:---> Straight
Car ID: 17, Approaching from:--> West road, Wants to turn:---> Left
                    1. Car ID: 958 and 103 are both allowed to pass simultaneously (Both going Straight / turning right).
-------------------------------------------------------------------------------------------------------------------------------------

                    Normal Sequence : North_Car is allowed to cross the junction -> East_Car,-> Southast_Car,-> West_Car in sequence.
-------------------------------------------------------------------------------------------------------------------------------------
```

6



```
Car ID: 364, Approaching from:--> North road, Wants to turn:---> Straight
Car ID: 561, Approaching from:--> East road, Wants to turn:---> Right
Car ID: 827, Approaching from:--> South road, Wants to turn:---> Straight
Car ID: 942, Approaching from:--> West road, Wants to turn:---> Right
                    1. Car ID: 364 and 827 are both allowed to pass simultaneously (Both going Straight / turning right).
-------------------------------------------------------------------------------------------------------------------------------------

                    Car ID: 561 and 942 are both allowed to pass simultaneously (Both going Straight / turning right).
-------------------------------------------------------------------------------------------------------------------------------------
```

Uppaal Automata