Final Project, SI1336

Carl Schiller, 9705266436

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Abstract

Contents

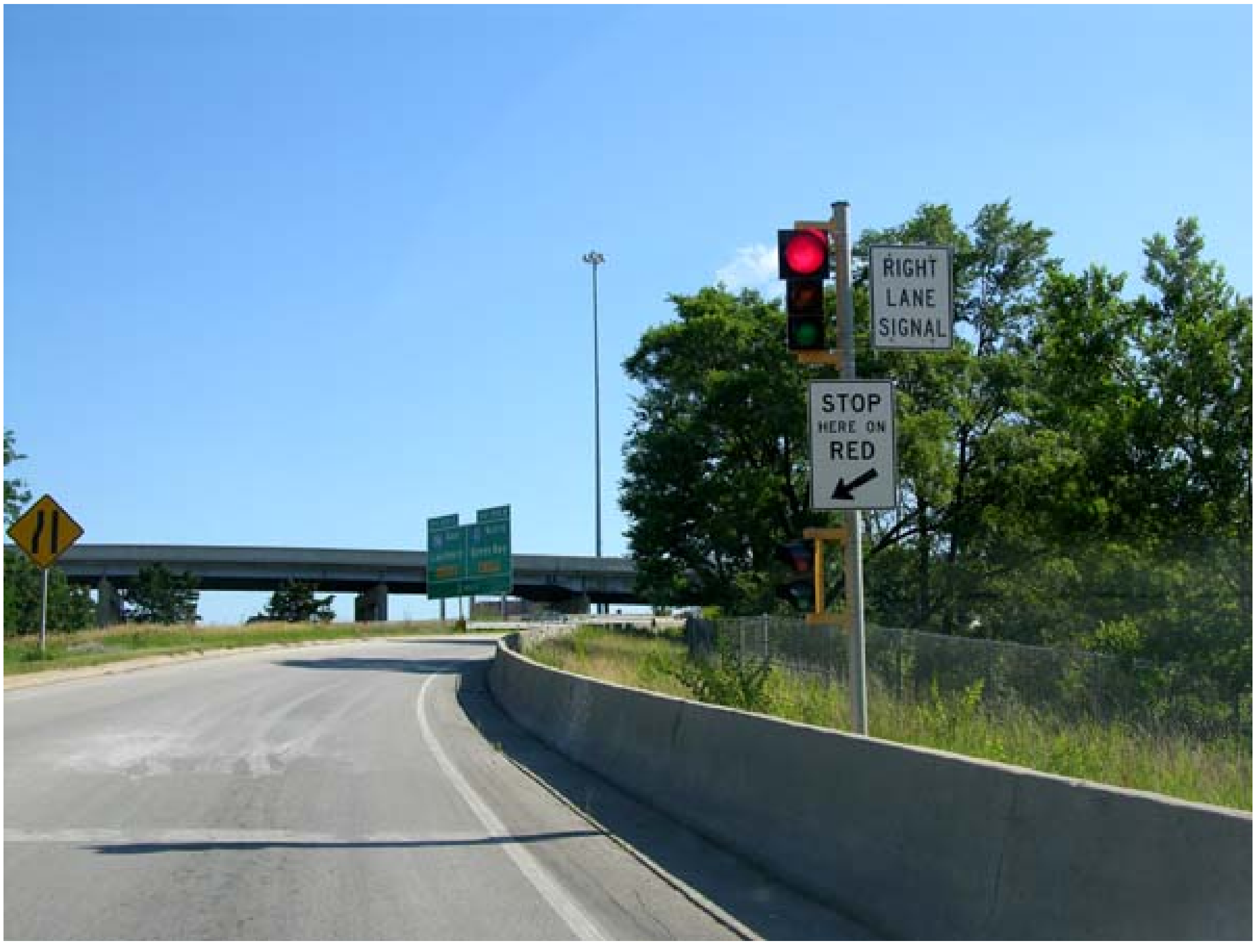


Figure 1: A typical ramp meter, image courtesy of [3]

1 Introduction

1.1 Problem formulation

This project is intended to simulate the traffic flow effect of a *time fixed ramp meter* a freeway on-ramp in Roslags Näsby trafikplats, Sweden. A *ramp meter* is a device that manages the flow of traffic onto the freeway, an example of a *ramp meter* can be seen in figure 1. More specifically, a *time fixed ramp meter* that only allow one car per green signal period will be examined. There are also more active variants of *ramp meters* which measure gaps in the traffic on the freeway to determine when to release vehicles, but this is beyond the scope of this project. Ramp metering systems have successfuly been proven to decrease congestion and reduce travel time on freeways. [4]

1.2 Complex systems

Traffic flow is a typical example of a complex system. As described in *An Introduction to Computer Simulation Methods Third Edition (revised)*, traffic flow can be simulated by modelling the system as a *Cellular Automaton*. A *Cellular Automaton* is a grid lattice which changes state on each tick based on rules and the current configuration of the lattice. [2]

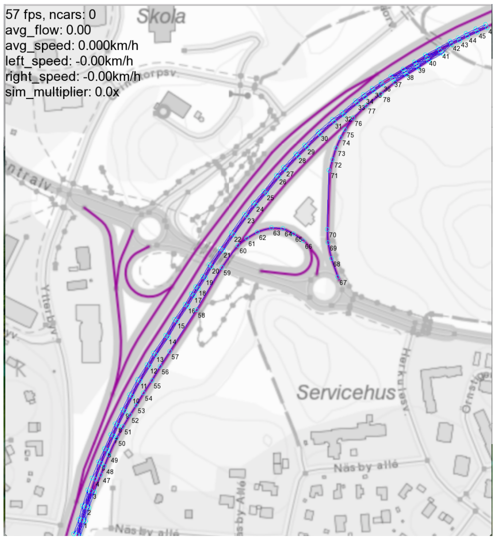
2 Method

Cellular Automata was determined to not be satisfactory when trying to model the flow of the freeway. This is because lane change and collision detection worked poorly on a grid lattice in two dimensions. Another approach was considered instead.

2.1 Graphs

In order to model the road with several lanes, a *directed graph* was implemented with blocks of vertices as lanes, with directed edges as paths for the cars to drive. In other terms, cars drive on "rails" and can only change lanes on specified vertices, as can be seen in figure 2. [1]

When using a *directed graph* instead of a grid lattice, collision avoidance becomes a lot easier to implement. Time complexity also decreases, which improves simulation performance. The collision avoidance method inmplemented is $\mathcal{O}(n \cdot m^2)$, where n is the amount of cars and m is the search area. The grid lattice as previously metioned had dimensions 550x600, which was replaced by a graph with approximately 140 edges which improved performance by approximately 2000 times (if the whole system is searched for potential obstructions i.e. other cars).



```
57 fps, ncars: 0
avg_flow: 0.00
avg_speed: 0.000km/h
left_speed: -0.00km/h
right_speed: -0.00km/h
sim_multiplier: 0.0x
```

Figure 2: Setup of road with vertices and edges.

2.2 Discretization

In contrast to *Cellular Automata* there is no grid discretization, and thus the cars run on continuous "tracks". The distance traveled by each car is determined by the individual car's speed and the system wide time step size, which has been capped at 1/60 seconds because of rendering considerations. Another benefit from the *directed graph* implementation is that the directions of the cars is not required as a parameter. All that is needed in order to simulate a car is the speed and the distance to the next vertex as well as knowing which vertex the car originated from. When stepping in time the distance traveled is subtracted from the distance to the next vertex, and when the car has reached the next vertex a new target vertex is selected.

Cars make decisions independently according to simple rules, and generates a complex behavior when interacting with each other i.e. braking or changing lanes.

2.3 Graphics rendering

When tweaking parameters involved in the cars' descision making, it is hard to get an overview of how each parameter influences the system wide behavior of the traffic. Thus a lot of effort has been spent on developing a graphical interface that shows how the traffic flows in the given configuration of parameters. An example of a test run is shown in the link below.

3 Result

4 Discussion

References

[1] *Gerichteter Graph*. de. Page Version ID: 179253516. July 2018. URL: https://de.wikipedia.org/w/index.php?title=Gerichteter_Graph&oldid=179253516 (visited on 03/05/2019).

[2] H Gould, J Tobochnik, and W Christian. "Introduction to Computer Simulation Methods". In: (), p. 797.

[3] Patriarca12. *English: Ramp meter on ramp from Miller Park Way to Interstate 94 east in Milwaukee, Wisconsin, USA*. July 2008. URL: https://commons.wikimedia.org/wiki/File:Ramp_meter_from_Miller_Park_Way_to_I-94_east_in_Milwaukee.jpg (visited on 03/05/2019).

[4] U.S. Department of Transportation, Federal Highway Administration. *Ramp Metering: A Proven, Cost-Effective Operational Strategy - AÂ Primer: 1. Overview of Ramp Metering*. URL: https://ops.fhwa.dot.gov/publications/fhwahop14020/sec1.htm (visited on 03/05/2019).

A Header files

A.1 cars.h

```
//
// Created by Carl Schiller on 2019-03-04.
//

#ifndef HIGHWAY_CAR_H
#define HIGHWAY_CAR_H

//////////////////////////////////////////////////////////////////////////
//                                                                      //
// Car                                                                  //
//                                                                      //
// Describes a car that moves around in Road class                      //
//                                                                      //
//////////////////////////////////////////////////////////////////////////

#include <map>
#include "roadnode.h"
#include "roadsegment.h"

class Car{
private:
    float m_dist_to_next_node;
    float m_speed;
    float m_theta; // radians

    float m_aggressiveness; // how fast to accelerate;
    float m_target_speed;

public:
    Car();
    ~Car();
    Car(RoadSegment * spawn_point, int lane, float vel, float target_speed, float
    agressivness);
    Car(RoadSegment * spawn_point, RoadNode * lane, float vel, float target_speed, float
    agressivness);

    // all are raw pointers
    RoadSegment * current_segment;
    RoadNode * current_node;
    RoadNode * heading_to_node;
    Car * overtake_this_car;

    void update_pos(float delta_t);
    void merge(std::vector<RoadNode*> & connections);
    void do_we_want_to_overtake(Car * & closest_car, int & current_lane);
    void accelerate(float delta_t);
    void avoid_collision(float delta_t);
    Car * find_closest_car_ahead();
    std::map<Car *,bool> find_cars_around_car();

    float x_pos();
    float y_pos();

    float & speed();
    float & target_speed();
    float & theta();

    RoadSegment * get_segment();
};

#endif //HIGHWAY_CAR_H
```

../highway/headers/car.h

A.2 road.h

```
//
// Created by Carl Schiller on 2019-03-04.
//

#ifndef HIGHWAY_ROAD_H
#define HIGHWAY_ROAD_H

/////////////////////////////////////////////////////////////////////////////
//                                                                         //
// Road                                                                    //
//                                                                         //
// Describes a road with interconnected nodes. Mathematically it is       //
// a graph.                                                                //
//                                                                         //
/////////////////////////////////////////////////////////////////////////////

#include "roadsegment.h"
#include <vector>
#include <string>

class Road{
private:
    std::vector<RoadSegment*> m_segments; // OWNERSHIP
    std::vector<RoadSegment*> m_spawn_positions; // raw pointers
    std::vector<RoadSegment*> m_despawn_positions; // raw pointers

    const std::string M_FILENAME;
private:
    Road();
    ~Road();
public:
    static Road &shared() {static Road road; return road;} // in order to only load road once in memory

    Road(const Road& copy) = delete; // no copying allowed
    Road& operator=(const Road& rhs) = delete; // no copying allowed

    bool load_road();
    std::vector<RoadSegment*> & spawn_positions();
    std::vector<RoadSegment*> & despawn_positions();
    std::vector<RoadSegment*> & segments();
};

#endif //HIGHWAY_ROAD_H
```

../highway/headers/road.h

A.3 roadnode.h

```
//
// Created by Carl Schiller on 2019-03-04.
//

#ifndef HIGHWAY_ROADNODE_H
#define HIGHWAY_ROADNODE_H

/////////////////////////////////////////////////////////////////////////////
//                                                                         //
// RoadNode                                                                //
//                                                                         //
// Describes the smallest element in Road, it is similar to                //
// that of a mathematical graph with nodes and edges.                      //
//                                                                         //
/////////////////////////////////////////////////////////////////////////////
```

```

#include <vector>
#include "car.h"
#include "roadsegment.h"

class RoadNode{
private:
    float m_x, m_y;
    std::vector<RoadNode*> m_nodes_from_me; // raw pointers, no ownership
    std::vector<RoadNode*> m_nodes_to_me;
    RoadSegment* m_is_child_of; // raw pointer, no ownership
public:
    RoadNode();
    ~RoadNode();
    RoadNode(float x, float y, RoadSegment * segment);

    void set_next_node(RoadNode *);
    void set_previous_node(RoadNode *);
    RoadSegment* get_parent_segment();
    RoadNode * get_next_node(int lane);
    std::vector<RoadNode*> & get_nodes_from_me();
    std::vector<RoadNode*> & get_nodes_to_me();
    float get_x();
    float get_y();
    float get_theta(RoadNode*);
};


#endif //HIGHWAY_ROADNODE_H
```

../highway/headers/roadnode.h

A.4 roadsegment.h

```
//
// Created by Carl Schiller on 2019-03-04.
//

#ifndef HIGHWAY_ROADSEGMENT_H
#define HIGHWAY_ROADSEGMENT_H

//////////////////////////////////////////////////////////////////////////
//                                                                      //
// RoadSegment                                                          //
//                                                                      //
// Describes a container for several RoadNodes                          //
//                                                                      //
//////////////////////////////////////////////////////////////////////////

#include <vector>

class RoadNode;

class Car;

class RoadSegment{
private:
    const float m_x, m_y;
    float m_theta;
    const int m_n_lanes;

    constexpr static float M_LANE_WIDTH = 4.0f;

    std::vector<RoadNode*> m_nodes; // OWNERSHIP
    RoadSegment * m_next_segment; // raw pointer, no ownership
public:
    RoadSegment() = delete;
    RoadSegment(float x, float y, RoadSegment * next_segment, int lanes);
    RoadSegment(float x, float y, float theta, int lanes);
    RoadSegment(float x, float y, int lanes, bool merge);
    ~RoadSegment(); // rule of three
    RoadSegment(const RoadSegment&) = delete; // rule of three
    RoadSegment& operator=(const RoadSegment& rhs) = delete; // rule of three

    bool merge;
    std::vector<Car*> m_cars; // raw pointer, no ownership

    RoadNode * get_node_pointer(int n);
    std::vector<RoadNode *> get_nodes();
    void append_car(Car*);
    void remove_car(Car*);
    RoadSegment * next_segment();
    float get_theta();
    const float get_x() const;
    const float get_y() const;

    int get_lane_number(RoadNode *);
    const int get_total_amount_of_lanes() const;
    void set_theta(float theta);
    void set_next_road_segment(RoadSegment*);
    void calculate_theta();
    void calculate_and_populate_nodes();
    void set_all_node_pointers_to_next_segment();
    void set_node_pointer_to_node(int from_node_n, int to_node_n, RoadSegment *);
};

#endif //HIGHWAY_ROADSEGMENT_H
```

../highway/headers/roadsegment.h

A.5 simulation.h

```
//
// Created by Carl Schiller on 2018-12-19.
//

#ifndef HIGHWAY_WINDOW_H
#define HIGHWAY_WINDOW_H

//////////////////////////////////////////////////////////////////////
//                                                                  //
// Simulation                                                       //
//                                                                  //
// Describes how to simulate Traffic class                          //
//                                                                  //
//////////////////////////////////////////////////////////////////////

#include <vector>
#include "SFML/Graphics.hpp"
#include "traffic.h"

class Simulation{
private:
    sf::Mutex * m_mutex;
    Traffic * m_traffic;
    bool * m_exit_bool;
    const int M_SIM_SPEED;
    const int M_FRAMERATE;
public:
    Simulation() = delete;
    Simulation(Traffic *& traffic,sf::Mutex *& mutex, int sim_speed, int m_framerate, bool *& exitbool);
    void update();
};


#endif //HIGHWAY_WINDOW_H
```

../highway/headers/simulation.h

A.6 traffic.h

```
//
// Created by Carl Schiller on 2018-12-19.
//

#ifndef HIGHWAY_TRAFFIC_H
#define HIGHWAY_TRAFFIC_H

//////////////////////////////////////////////////////////////////////////
//                                                                      //
// Traffic                                                              //
//                                                                      //
// Describes the whole traffic situation with Cars and a Road.          //
// Inherits form SFML Graphics.hpp in order to render the cars.         //
//                                                                      //
//////////////////////////////////////////////////////////////////////////

#include <random>
#include <vector>
#include "SFML/Graphics.hpp"
#include "car.h"

class Traffic : public sf::Drawable, public sf::Transformable{
private:
    std::vector<Car*> m_cars;
    bool debug;
    std::mt19937 & my_engine();
    sf::Font m_font;

public:
    Traffic();
    explicit Traffic(bool debug);
    ~Traffic();
    Traffic(const Traffic&); // rule of three
    Traffic& operator=(const Traffic&); // rule of three

    unsigned long n_of_cars();
    void spawn_cars(double & spawn_counter, float elapsed, double & threshold);
    void despawn_cars();
    void despawn_all_cars();
    void despawn_car(Car*& car);
    void force_place_car(RoadSegment * seg, RoadNode * node, float vel, float target, float aggro);


    void update(float elapsed_time);
    std::vector<Car *> get_car_copies() const;
    float get_avg_flow();
    std::vector<float> get_avg_speeds();
private:
    virtual void draw(sf::RenderTarget& target, sf::RenderStates states) const;
public:
    void get_info(sf::Text & text, sf::Time &elapsed);
    double m_multiplier;
};
```

```
#endif //HIGHWAY_TRAFFIC_H
```

../highway/headers/traffic.h

A.7 unittests.h

```
//
// Created by Carl Schiller on 2019-01-16.
//


#ifndef HIGHWAY_UNITTESTS_H
#define HIGHWAY_UNITTESTS_H

//////////////////////////////////////////////////////////////////////////
//                                                                      //
// Tests                                                                //
//                                                                      //
// Testing the various functions.                                       //
//                                                                      //
//////////////////////////////////////////////////////////////////////////

#include ”traffic.h”
#include ”SFML/Graphics.hpp”

class Tests{
private:
    Traffic * m_traffic;
    sf::Mutex * m_mutex;
    void placement_test();
    void delete_cars_test();
    void run_one_car();
    void placement_test_2();
    void placement_test_3();
public:
    Tests() = delete;
    Tests(Traffic *& traffic, sf::Mutex *& mutex);

    void run_all_tests();
};

#endif //HIGHWAY_UNITTESTS_H
```

../highway/headers/unittests.h

A.8 util.h

```
//
// Created by Carl Schiller on 2019-03-04.
//

#ifndef HIGHWAY_UTIL_H
#define HIGHWAY_UTIL_H

//////////////////////////////////////////////////////////////////////////
//                                                                      //
// Util                                                                 //
//                                                                      //
// Help functions for Car class.                                        //
//                                                                      //
//////////////////////////////////////////////////////////////////////////

#include ”car.h”
```

```
class Util{
public:
    static std::vector<std::string> split_string_by_delimiter(const std::string & str, const
     char delim);
    static bool is_car_behind(Car * a, Car * b);
    static bool will_car_paths_cross(Car *a, Car*b);
    static float distance_to_car(Car * a, Car * b);
    static float get_min_angle(float ang1, float ang2);
    static float distance(float x1, float x2, float y1, float y2);
};

#endif //HIGHWAY_UTIL_H
```

../highway/headers/util.h

B Source files

B.1 cars.cpp

```
//
// Created by Carl Schiller on 2019-03-04.
//

#include "../headers/car.h"
#include <map>
#include <cmath>
#include <list>
#include "../headers/util.h"

////////////////////////////////////////////////////////////////////////////////
/// Constructor.

Car::Car() = default;

////////////////////////////////////////////////////////////////////////////////
/// Constructor for new car with specified lane numbering in spawn point.
/// Lane numbering @param lane must not exceed amount of lanes in
/// @param spawn_point, otherwise an exception will be thrown.

Car::Car(RoadSegment *spawn_point, int lane, float vel, float target_speed, float
    aggressivness):
        m_speed(vel),
        m_aggressiveness(aggressivness),
        m_target_speed(target_speed),
        current_segment(spawn_point),
        current_node(current_segment->get_node_pointer(lane)),
        overtake_this_car(nullptr)
{
    current_segment->append_car(this);

    if(!current_node->get_nodes_from_me().empty()){
        heading_to_node = current_node->get_next_node(lane);

        m_dist_to_next_node = Util::distance(current_node->get_x(),heading_to_node->get_x(),
    current_node->get_y(),heading_to_node->get_y());

        m_theta = current_node->get_theta(heading_to_node);
    }
    else{
        throw std::invalid_argument("Car spawns in node with empty connections, or with a
    nullptr segment");
    }
}

////////////////////////////////////////////////////////////////////////////////
```

```
/// Constructor for new car with specified lane. Note that
/// @param lane must be in @param spawn_point, otherwise no guarantee on
/// functionality.

Car::Car(RoadSegment *spawn_point, RoadNode *lane, float vel, float target_speed, float
    agressivness) :
        m_speed(vel),
        m_aggressiveness(agressivness),
        m_target_speed(target_speed),
        current_segment(spawn_point),
        current_node(lane),
        overtake_this_car(nullptr)
{
    current_segment->append_car(this);

    if(!current_node->get_nodes_from_me().empty() || current_segment->next_segment() !=
    nullptr){
        heading_to_node = current_node->get_next_node(0);

        m_dist_to_next_node = Util::distance(current_node->get_x(),heading_to_node->get_x(),
    current_node->get_y(),heading_to_node->get_y());

        m_theta = current_node->get_theta(heading_to_node);
    }
    else{
        throw std::invalid_argument("Car spawns in node with empty connections, or with a
    nullptr segment");
    }
}

///////////////////////////////////////////////////////////////////////////////
/// Destructor for car.

Car::~Car(){
    if(this->current_segment != nullptr){
        this->current_segment->remove_car(this); // remove this pointer shit
    }

    overtake_this_car = nullptr;
    current_segment = nullptr;
    heading_to_node = nullptr;
    current_node = nullptr;

}

///////////////////////////////////////////////////////////////////////////////
/// Updates position for car with time step @param delta_t.

void Car::update_pos(float delta_t) {
    m_dist_to_next_node -= m_speed*delta_t;
    // if we are at a new node.

    if(m_dist_to_next_node < 0){
        current_segment->remove_car(this); // remove car from this segment
        current_segment = heading_to_node->get_parent_segment(); // set new segment
        if(current_segment != nullptr){
            current_segment->append_car(this); // add car to new segment
        }
        current_node = heading_to_node; // set new current node as previous one.

        //TODO: place logic for choosing next node
        std::vector<RoadNode*> connections = current_node->get_nodes_from_me();

        if(!connections.empty()){

            merge(connections);

            m_dist_to_next_node += Util::distance(current_node->get_x(),heading_to_node->
    get_x(),current_node->get_y(),heading_to_node->get_y());
            m_theta = current_node->get_theta(heading_to_node);

        }
    }
}

////////////////////////////////////////////////////////////////////////////////
/// Function to determine if we can merge into another lane depending on.
/// properties of @param connections.

void Car::merge(std::vector<RoadNode*> & connections) {
    // check if we merge
    int current_lane = current_segment->get_lane_number(current_node);
    bool can_merge = true;
    std::map<Car*,bool> cars_around_car = find_cars_around_car();
    Car * closest_car = find_closest_car_ahead();

    for(auto it : cars_around_car){
        float delta_dist = Util::distance_to_car(it.first,this);
        float delta_speed = abs(speed()-it.first->speed());

        if(current_lane == 0 && it.first->heading_to_node->get_parent_segment()->
    get_lane_number(it.first->heading_to_node) == 1 ){
            can_merge =
                    delta_dist > std::max(delta_speed*4.0f/m_aggressiveness,15.0f);
        }
        else if(current_lane == 1 && it.first->heading_to_node->get_parent_segment()->
    get_lane_number(it.first->heading_to_node) == 0){
            can_merge =
                    delta_dist > std::max(delta_speed*4.0f/m_aggressiveness,15.0f);
        }

        if(!can_merge){
            break;
        }
    }

    if(current_segment->merge){
        if(current_lane == 0 && connections[0]->get_parent_segment()->
    get_total_amount_of_lanes() != 2){
            if(can_merge){
                heading_to_node = connections[1];
            }
            else{
                heading_to_node = connections[0];
            }
        }
        else if(connections[0]->get_parent_segment()->get_total_amount_of_lanes() == 2){
            current_lane = std::max(current_lane-1,0);
            heading_to_node = connections[current_lane];
        }
        else{
            heading_to_node = connections[current_lane];
        }
    }
        // if we are in start section
    else if(current_segment->get_total_amount_of_lanes() == 3){
        if(connections.size() == 1){
            heading_to_node = connections[0];
        }
        else{
            heading_to_node = connections[current_lane];
        }
    }
        // if we are in middle section
    else if(current_segment->get_total_amount_of_lanes() == 2){
        // normal way
        if(connections[0]->get_parent_segment()->get_total_amount_of_lanes() == 2){
            // check if we want to overtake car in front
            do_we_want_to_overtake(closest_car,current_lane);

            // commited to overtaking
            if(overtake_this_car != nullptr){
                if(current_lane != 1){
                    if(can_merge){
                        heading_to_node = connections[1];
                    }
                    else{
                        heading_to_node = connections[current_lane];
                    }
                }
                else{
                    heading_to_node = connections[current_lane];
                }

            }
                // merge back if overtake this car is nullptr.
            else{
                if(can_merge){
                    heading_to_node = connections[0];
                }
                else{
                    heading_to_node = connections[current_lane];
                }
            }

        }
        else{
            heading_to_node = connections[0];
        }
    }
    else if(current_segment->get_total_amount_of_lanes() == 1){
        heading_to_node = connections[0];
    }
}

////////////////////////////////////////////////////////////////////////////////
/// Helper function to determine if this car wants to overtake
/// @param closest_car.

void Car::do_we_want_to_overtake(Car * & closest_car, int & current_lane) {
    //see if we want to overtake car.

    if(closest_car != nullptr){
        //float delta_speed = closest_car->speed()-speed();
        float delta_distance = Util::distance_to_car(this,closest_car);

        if(overtake_this_car == nullptr){
            if(delta_distance > 10 && delta_distance < 40 && (target_speed()/closest_car->
    target_speed() > m_aggressiveness*1.0f ) && current_lane == 0 && closest_car->
    current_node->get_parent_segment()->get_lane_number(closest_car->current_node) == 0){
                overtake_this_car = closest_car;
            }
        }

    }

    if(overtake_this_car !=nullptr){
        if(Util::is_car_behind(overtake_this_car,this) && (Util::distance_to_car(this,
    overtake_this_car) > 30)){
            overtake_this_car = nullptr;
        }
    }
}
```

```

////////////////////////////////////////////////////////////////////////////////
/// Function to accelerate this car.

void Car::accelerate(float elapsed){
    float target = m_target_speed;
    float d_vel; // proportional control.

    if(m_speed < target*0.75){
        d_vel = m_aggressiveness*elapsed*2.0f;
    }
    else{
        d_vel = m_aggressiveness*(target-m_speed)*4*elapsed*2.0f;
    }

    m_speed += d_vel;
}

////////////////////////////////////////////////////////////////////////////////
/// Helper function to avoid collision with another car.

void Car::avoid_collision(float delta_t) {
    float min_distance = 8.0f; // for car distance.
    float ideal = min_distance+min_distance*(m_speed/20.f);

    Car * closest_car = find_closest_car_ahead();
    float detection_distance = m_speed*5.0f;

    if(closest_car != nullptr) {
        float radius_to_car = Util::distance_to_car(this, closest_car);
        float delta_speed = closest_car->speed() - this->speed();

        if (radius_to_car < ideal && delta_speed < 0 && radius_to_car > min_distance) {
            m_speed -= std::max(std::max((radius_to_car-min_distance)*0.5f,0.0f),10.0f*
    delta_t);
        }
        else if(radius_to_car < min_distance){
            m_speed -= std::max(std::max((min_distance-radius_to_car)*0.5f,0.0f),2.0f*
    delta_t);
        }
        else if(delta_speed < 0 && radius_to_car < detection_distance){
            m_speed -= std::min(
                    abs(pow(delta_speed, 2.0f)) * pow(ideal * 0.25f / radius_to_car, 2.0f) *
     m_aggressiveness * 0.15f,
                    10.0f * delta_t);
        }
        else {
            accelerate(delta_t);
        }

        if(current_segment->merge){
            std::map<Car*,bool> around = find_cars_around_car();
            for(auto it : around){
                float delta_dist = Util::distance_to_car(it.first,this);
                delta_speed = abs(speed()-it.first->speed());

                if(it.first->current_node->get_parent_segment()->get_lane_number(it.first->
    current_node) == 0 && delta_dist < ideal && this->current_segment->get_lane_number(
    current_node) == 1 && speed()/target_speed() > 0.5){
                    if(Util::is_car_behind(it.first,this)){
                        accelerate(delta_t);
                    }
                    else{
                        m_speed -= std::max(std::max((ideal-delta_dist)*0.5f,0.0f),10.0f*
    delta_t);
                    }
                }
                else if(it.first->current_node->get_parent_segment()->get_lane_number(it.first->current_node) == 1 && this->current_segment->get_lane_number(current_node) == 0 && speed()/target_speed() > 0.5 && delta_dist < ideal){
                    if(Util::is_car_behind(this,it.first)){
                        m_speed -= std::max(std::max((ideal-delta_dist)*0.5f,0.0f),10.0f*delta_t);
                    }
                    else{
                        accelerate(delta_t);
                    }
                }
            }
        }
        else{

        }
    }
    else{
        accelerate(delta_t);
    }

    if(m_speed < 0){
        m_speed = 0;
    }


}

////////////////////////////////////////////////////////////////////////////////
/// Helper function to find closest car in the same lane ahead of this car.
/// Returns a car if found, otherwise nullptr.

Car* Car::find_closest_car_ahead() {
    float search_radius = 50;
    std::map<RoadNode*,bool> visited;
    std::list<RoadNode*> queue;

    for(RoadNode * node : (this->current_segment->get_nodes())){
        queue.push_front(node);
    }

    Car* answer = nullptr;

    float shortest_distance = 10000000;

    while(!queue.empty()){
        RoadNode * next_node = queue.back(); // get last element
        queue.pop_back(); // remove element

        if(next_node != nullptr){
            if(!visited[next_node] && Util::distance(x_pos(),next_node->get_x(),y_pos(),next_node->get_y()) < search_radius){
                visited[next_node] = true;

                for(Car * car : next_node->get_parent_segment()->m_cars){
                    if(this != car){
                        float radius = Util::distance_to_car(this,car);
                        if(Util::is_car_behind(this,car) && Util::will_car_paths_cross(this,car) && radius < shortest_distance){
                            shortest_distance = radius;
                            answer = car;
                        }

                    }
                }

                // push in new nodes in front of list.
                for(RoadNode * node : next_node->get_nodes_from_me()){
                    queue.push_front(node);
                }
            }
        }
    }
    return answer;
}

////////////////////////////////////////////////////////////////////////////////
/// Searches for cars around this car in a specified radius. Note that
/// search radius is the radius to RoadNodes, and not surrounding cars.
/// Returns a map of cars the function has found.

std::map<Car *,bool> Car::find_cars_around_car() {
    const float search_radius = 40;
    std::map<RoadNode*,bool> visited;
    std::list<RoadNode*> queue;

    for(RoadNode * node : (this->current_segment->get_nodes())){
        queue.push_front(node);
    }

    std::map<Car *,bool> answer;
    while(!queue.empty()){
        RoadNode * next_node = queue.back(); // get last element
        queue.pop_back(); // remove element

        if(next_node != nullptr){
            if(!visited[next_node] && Util::distance(x_pos(),next_node->get_x(),y_pos(),
    next_node->get_y()) < search_radius){
                visited[next_node] = true;
                for(Car * car : next_node->get_parent_segment()->m_cars){
                    if(this != car){
                        answer[car] = true;
                    }
                }
                // push in new nodes in front of list.
                for(RoadNode * node : next_node->get_nodes_from_me()){
                    queue.push_front(node);
                }

                for(RoadNode * node: next_node->get_nodes_to_me()){
                    queue.push_front(node);
                }
            }
        }
    }
    return answer;
}

////////////////////////////////////////////////////////////////////////////////
/// Returns x position of car.

float Car::x_pos() {
    float x_position;
    if(heading_to_node != nullptr){
        x_position = heading_to_node->get_x()-m_dist_to_next_node*cos(m_theta);
    }
    else{
        x_position = current_node->get_x();
    }

    return x_position;
}

////////////////////////////////////////////////////////////////////////////////
/// Returns y position of car.

```

```
float Car::y_pos() {
    float y_position;
    if(heading_to_node != nullptr){
        y_position = heading_to_node->get_y()+m_dist_to_next_node*sin(m_theta);
    }
    else{
        y_position = current_node->get_y();
    }

    return y_position;
}

///////////////////////////////////////////////////////////////////////////////
/// Returns speed of car, as reference.

float & Car::speed() {
    return m_speed;
}

///////////////////////////////////////////////////////////////////////////////
/// Returns target speed of car as reference.

float & Car::target_speed() {
    return m_target_speed;
}

///////////////////////////////////////////////////////////////////////////////
/// Returns theta of car, the direction of the car. Defined in radians as a
/// mathematitan would define angles.

float & Car::theta() {
    return m_theta;
}

///////////////////////////////////////////////////////////////////////////////
/// Returns current segment car is in.

RoadSegment* Car::get_segment() {
    return current_segment;
}
```

../highway/cppfiles/car.cpp

B.2 main.cpp

```
#include <iostream>
#include <vector>
#include ”SFML/Graphics.hpp”
#include ”../headers/simulation.h”
#include ”../headers/unittests.h”
#include ”../headers/screens.h”

int main() {
    std::vector<cScreen*> Screens;
    int screen = 0;

    sf::RenderWindow App(sf::VideoMode(550*2, 600*2), ”Highway”);
    App.setFramerateLimit(60);

    screen_0 s0;
    Screens.push_back(&s0);
    screen_1 s1;
    Screens.push_back(&s1);

    while(screen >= 0){
        screen = Screens[screen]->Run(App);
    }

    return 0;
}
```

../highway/cppfiles/main.cpp

B.3 road.cpp

```
//
// Created by Carl Schiller on 2019-03-04.
//

#include "../headers/road.h"
#include <fstream>
#include <vector>
#include "../headers/roadsegment.h"
#include <iostream>
#include "../headers/util.h"

////////////////////////////////////////////////////////////////////////////////
/// Constructor of Road.

Road::Road() :
        M_FILENAME("../road.txt")
{
    if(!load_road()){
        std::cout << "Error in loading road.\n";
    };
}

////////////////////////////////////////////////////////////////////////////////
/// Destructor of Road.

Road::~Road() {
    for(RoadSegment * seg : m_segments){
        delete seg;
    }
    m_segments.clear();
}

////////////////////////////////////////////////////////////////////////////////
/// Function to load Road from txt file. Parsing as follows:
///
/// # ignores current line input.
///
/// If there are 4 tokens in current line:
/// tokens[0]: segment number
/// tokens[1]: segment x position
/// tokens[2]: segment y position
/// tokens[3]: amount of lanes
///
/// If there are 5 tokens in current line:
/// tokens[0]: segment number
/// tokens[1]: segment x position
/// tokens[2]: segment y position
/// tokens[3]: amount of lanes
/// tokens[4]: spawn point or if it's a merging lane (true/false/merge)
///
/// If there are 4+3*n tokens in current line:
/// tokens[0]: segment number
/// tokens[1]: segment x position
/// tokens[2]: segment y position
/// tokens[3]: amount of lanes
/// tokens[3+3*n]: from lane number of current segment
/// tokens[4+3*n]: to lane number of segment specified in next token (below)
/// tokens[5+3*n]: to segment number.

bool Road::load_road() {
    bool loading = true;
    std::ifstream stream;
    stream.open(M_FILENAME);

    std::vector<std::vector<std::string>> road_vector;
    road_vector.reserve(100);

    if(stream.is_open()){
        std::string line;
        std::vector<std::string> tokens;
        while(std::getline(stream,line)){
            tokens = Util::split_string_by_delimiter(line,' ');
            if(tokens[0] != "#"){
                road_vector.push_back(tokens);
            }
        }
    }
    else{
        loading = false;
    }


    // load segments into memory.
    for(std::vector<std::string> & vec : road_vector){
        if(vec.size() == 5){
            if(vec[4] == "merge"){
                RoadSegment * seg = new RoadSegment(std::stof(vec[1]),std::stof(vec[2]),std::stoi(vec[3]),true);
                m_segments.push_back(seg);
            }
            else{
                RoadSegment * seg = new RoadSegment(std::stof(vec[1]),std::stof(vec[2]),std::stoi(vec[3]),false);
                m_segments.push_back(seg);
            }
        }
        else{
            RoadSegment * seg = new RoadSegment(std::stof(vec[1]),std::stof(vec[2]),std::stoi(vec[3]),false);
            m_segments.push_back(seg);
        }

    }


    // populate nodes.
    for (int i = 0; i < m_segments.size(); ++i) {
        // populate nodes normally.
        if(road_vector[i].size() == 4){
            m_segments[i]->set_next_road_segment(m_segments[i+1]);
            m_segments[i]->calculate_theta();
            // calculate nodes based on theta.
            m_segments[i]->calculate_and_populate_nodes();

        }
        else if(road_vector[i].size() == 5){
            if(road_vector[i][4] == "false"){
                // take previous direction and populate nodes.
                m_segments[i]->set_theta(m_segments[i-1]->get_theta());
                m_segments[i]->calculate_and_populate_nodes();
                // but do not connect nodes to new ones.

                // make this a despawn segment
                m_despawn_positions.push_back(m_segments[i]);
            }
            else if(road_vector[i][4] == "true"){
                m_segments[i]->set_next_road_segment(m_segments[i+1]);
                m_segments[i]->calculate_theta();
                // calculate nodes based on theta.
                m_segments[i]->calculate_and_populate_nodes();

                // make this a spawn segment
                m_spawn_positions.push_back(m_segments[i]);
            }
            else if(road_vector[i][4] == "merge"){
                m_segments[i]->set_next_road_segment(m_segments[i+1]);
                m_segments[i]->calculate_theta();
                // calculate nodes based on theta.
                m_segments[i]->calculate_and_populate_nodes();
            }

        }
            // else we connect one by one.
        else{
            // take previous direction and populate nodes.
            m_segments[i]->set_theta(m_segments[i-1]->get_theta());
            // calculate nodes based on theta.
            m_segments[i]->calculate_and_populate_nodes();
        }
    }

    // connect nodes.
    for (int i = 0; i < m_segments.size(); ++i) {
        // do normal connection, ie connect all nodes.
        if(road_vector[i].size() == 4){
            m_segments[i]->set_all_node_pointers_to_next_segment();
        }
        else if(road_vector[i].size() == 5){
            if(road_vector[i][4] == "false"){
                // but do not connect nodes to new ones.
            }
            else if(road_vector[i][4] == "true"){
                m_segments[i]->set_all_node_pointers_to_next_segment();
            }
            else if(road_vector[i][4] == "merge"){
                m_segments[i]->set_all_node_pointers_to_next_segment();
            }

        }
            // else we connect one by one.
        else{
            // manually connect nodes.
            int amount_of_pointers = (int)road_vector[i].size()-4;
            for(int j = 0; j < amount_of_pointers/3; j++){
                int current_pos = 4+j*3;
                RoadSegment * next_segment = m_segments[std::stoi(road_vector[i][current_pos
    +2])];
                m_segments[i]->set_node_pointer_to_node(std::stoi(road_vector[i][current_pos
    ]),std::stoi(road_vector[i][current_pos+1]),next_segment);
            }
        }
    }
    return loading;
}

////////////////////////////////////////////////////////////////////////////////
/// Returns spawn positions of Road

std::vector<RoadSegment*>& Road::spawn_positions() {
    return m_spawn_positions;
}

////////////////////////////////////////////////////////////////////////////////
```

```cpp
/// Returns despawn positions of Road

std::vector<RoadSegment*>& Road::despawn_positions() {
    return m_despawn_positions;
}

///////////////////////////////////////////////////////////////////////////
/// Returns all segments of Road.

std::vector<RoadSegment*>& Road::segments() {
    return m_segments;
}
```

../highway/cppfiles/road.cpp

B.4 roadnode.cpp

```cpp
//
// Created by Carl Schiller on 2019-03-04.
//

#include "../headers/roadnode.h"
#include <cmath>

///////////////////////////////////////////////////////////////////////////
/// Constructor

RoadNode::RoadNode() = default;

///////////////////////////////////////////////////////////////////////////
/// Destructor

RoadNode::~RoadNode() = default;

///////////////////////////////////////////////////////////////////////////
/// Constructor, @param x is x position of node, @param y is y position of node,
/// @param segment is to which segment this RoadNode belongs.

RoadNode::RoadNode(float x, float y, RoadSegment * segment) {
    m_x = x;
    m_y = y;
    m_is_child_of = segment;
}

///////////////////////////////////////////////////////////////////////////
/// Appends a new RoadNode to the list connections from this RoadNode.
/// I.e. to where a Car is allowed to drive.

void RoadNode::set_next_node(RoadNode * next_node) {
    m_nodes_from_me.push_back(next_node);
    next_node->m_nodes_to_me.push_back(this); // sets double linked chain.
}

///////////////////////////////////////////////////////////////////////////
/// Appends a new RoadNode to the list connections to this RoadNode.
/// I.e. from where a Car is allowed to drive to this Node.

void RoadNode::set_previous_node(RoadNode * prev_node) {
    m_nodes_to_me.push_back(prev_node);
}

///////////////////////////////////////////////////////////////////////////
/// Returns RoadSegment to which this RoadNode belongs.

RoadSegment* RoadNode::get_parent_segment() {
    return m_is_child_of;
}

///////////////////////////////////////////////////////////////////////////////
/// Returns connections from this RoadNode.

std::vector<RoadNode*> & RoadNode::get_nodes_from_me() {
    return m_nodes_from_me;
}

///////////////////////////////////////////////////////////////////////////////
/// Returns connections to this RoadNode.

std::vector<RoadNode*>& RoadNode::get_nodes_to_me() {
    return m_nodes_to_me;
}

///////////////////////////////////////////////////////////////////////////////
/// Returns x position of RoadNode.

float RoadNode::get_x() {
    return m_x;
}

///////////////////////////////////////////////////////////////////////////////
/// Returns y position of RoadNode.

float RoadNode::get_y() {
    return m_y;
}

///////////////////////////////////////////////////////////////////////////////
/// Returns angle of this RoadNode to @param node as a mathematitian
/// would define angles. In radians.

float RoadNode::get_theta(RoadNode* node) {
    for(RoadNode * road_node : m_nodes_from_me){
        if(node == road_node){
            return atan2(m_y-node->m_y,node->m_x-m_x);
        }
    }
    throw std::invalid_argument("Node given is not a connecting node");
}

///////////////////////////////////////////////////////////////////////////////
/// Returns RoadNode according to @param lane from the vector of node
/// connections from this RoadNode.

RoadNode* RoadNode::get_next_node(int lane) {
    return m_nodes_from_me[lane];
}
```

../highway/cppfiles/roadnode.cpp

B.5 roadsegment.cpp

```
//
// Created by Carl Schiller on 2019-03-04.
//

#include "../headers/roadsegment.h"
#include "../headers/roadnode.h"
#include <cmath>

///////////////////////////////////////////////////////////////////////////////
/// RoadSegment destructor, removes all RodeNode element children because of
/// ownership.
```

```
RoadSegment::~RoadSegment(){
    for(RoadNode * elem : m_nodes){
        delete elem;
    }
    m_nodes.clear();
}

///////////////////////////////////////////////////////////////////////////////
/// Constructor, creates a new segment with next connecting segment as
/// @param next_segment

RoadSegment::RoadSegment(float x, float y, RoadSegment * next_segment, int lanes):
        m_x(x),
        m_y(y),
        m_n_lanes(lanes),
        m_next_segment(next_segment)
{
    m_theta = atan2(m_y-m_next_segment->m_y,m_next_segment->m_x-m_x);

    m_nodes.reserve(m_n_lanes);

    calculate_and_populate_nodes(); // populates segment with RoadNodes.
}

///////////////////////////////////////////////////////////////////////////////
/// Constructor, creates a new segment with manually entered @param theta.

RoadSegment::RoadSegment(float x, float y, float theta, int lanes) :
        m_x(x),
        m_y(y),
        m_theta(theta),
        m_n_lanes(lanes),
        m_next_segment(nullptr)
{
    m_nodes.reserve(m_n_lanes);

    calculate_and_populate_nodes(); // populates segment with RoadNodes.
}

///////////////////////////////////////////////////////////////////////////////
/// Constructor, creates a new segment without creating RoadNodes. This
/// needs to be done manually with functions below.

RoadSegment::RoadSegment(float x, float y, int lanes, bool mer):
        m_x(x),
        m_y(y),
        m_n_lanes(lanes),
        m_next_segment(nullptr),
        merge(mer)
{
    m_nodes.reserve(m_n_lanes);

    // can't set nodes if we don't have a theta.
}

///////////////////////////////////////////////////////////////////////////////
/// Returns theta (angle) of RoadSegment, in which direction the segment points

float RoadSegment::get_theta() {
    return m_theta;
}

///////////////////////////////////////////////////////////////////////////////
/// Returns x position of RoadSegment.

const float RoadSegment::get_x() const{
    return m_x;
```

```
}

////////////////////////////////////////////////////////////////////////////////
/// Returns y position of RoadSegment.

const float RoadSegment::get_y() const {
    return m_y;
}

////////////////////////////////////////////////////////////////////////////////
/// Returns int number of @param node. E.g. 0 would be the right-most lane.
/// Throws exception if we do not find the node in this segment.

int RoadSegment::get_lane_number(RoadNode * node) {
    for(int i = 0; i < m_n_lanes; i++){
        if(node == m_nodes[i]){
            return i;
        }
    }
    throw std::invalid_argument("Node is not in this segment");
}

////////////////////////////////////////////////////////////////////////////////
/// Adds a new car to the segment.

void RoadSegment::append_car(Car * car) {
    m_cars.push_back(car);
}

////////////////////////////////////////////////////////////////////////////////
/// Removes car from segment, if car is not in list we do nothing.

void RoadSegment::remove_car(Car * car) {
    unsigned long size = m_cars.size();
    bool found = false;
    for(int i = 0; i < size; i++){
        if(car == m_cars[i]){
            m_cars[i] = nullptr;
            found = true;
        }
    }
    std::vector<Car*>::iterator new_end = std::remove(m_cars.begin(),m_cars.end(),
    static_cast<Car*>(nullptr));
    m_cars.erase(new_end,m_cars.end());

    /*
    if(!found){
        throw std::invalid_argument("Car is not in this segment.");
    }
    */
}

////////////////////////////////////////////////////////////////////////////////
/// Sets theta of RoadSegment according to @param theta.

void RoadSegment::set_theta(float theta) {
    m_theta = theta;
}

////////////////////////////////////////////////////////////////////////////////
/// Automatically populates segment with nodes according to amount of lanes
/// specified and theta specified.

void RoadSegment::calculate_and_populate_nodes() {
    // calculates placement of nodes.
    float total_length = M_LANE_WIDTH*(m_n_lanes-1);
    float current_length = -total_length/2.0f;

    for(int i = 0; i < m_n_lanes; i++){
        float x_pos = m_x+current_length*cos(m_theta+(float)M_PI*0.5f);
        float y_pos = m_y-current_length*sin(m_theta+(float)M_PI*0.5f);
        m_nodes.push_back(new RoadNode(x_pos,y_pos,this));
        current_length += M_LANE_WIDTH;
    }
}

////////////////////////////////////////////////////////////////////////////////
/// Sets next segment to @param next_segment

void RoadSegment::set_next_road_segment(RoadSegment * next_segment) {
    m_next_segment = next_segment;
}

////////////////////////////////////////////////////////////////////////////////
/// Calculates theta according to next_segment. Throws if m_next_segment is
/// nullptr

void RoadSegment::calculate_theta() {
    if(m_next_segment == nullptr){
        throw std::invalid_argument("Can't calculate theta if next segment is nullptr");
    }
    m_theta = atan2(m_y-m_next_segment->m_y,m_next_segment->m_x-m_x);
}

////////////////////////////////////////////////////////////////////////////////
/// Returns node of lane number n. E.g. n=0 is the right-most lane.

RoadNode* RoadSegment::get_node_pointer(int n) {
    return m_nodes[n];
}

////////////////////////////////////////////////////////////////////////////////
/// Returns all nodes in segment.

std::vector<RoadNode *> RoadSegment::get_nodes() {
    return m_nodes;
}

////////////////////////////////////////////////////////////////////////////////
/// Returns next segment

RoadSegment* RoadSegment::next_segment() {
    return m_next_segment;
}

////////////////////////////////////////////////////////////////////////////////
/// Automatically populates node connections by connecting current node to
/// all nodes in next segment.

void RoadSegment::set_all_node_pointers_to_next_segment() {
    for(RoadNode * node: m_nodes){
        for(int i = 0; i < m_next_segment->m_n_lanes; i++){
            node->set_next_node(m_next_segment->get_node_pointer(i));
        }
    }
}

////////////////////////////////////////////////////////////////////////////////
/// Manually set connection to next segment's node. No guarantee is made
/// on @param from_node_n and @param to_node_n. Can crash if index out of range.

void RoadSegment::set_node_pointer_to_node(int from_node_n, int to_node_n, RoadSegment *
    next_segment) {
    RoadNode * pointy = next_segment->get_node_pointer(to_node_n);
    m_nodes[from_node_n]->set_next_node(pointy);
}
```

```

////////////////////////////////////////////////////////////////////////////////
/// Returns amount of lanes in this segment.

const int RoadSegment::get_total_amount_of_lanes() const {
    return m_n_lanes;
}
```

../highway/cppfiles/roadsegment.cpp

B.6 simulation.cpp

```
//
// Created by Carl Schiller on 2018-12-19.
//

#include <iostream>
#include "../headers/traffic.h"
#include "../headers/simulation.h"
#include <cmath>
#include <unistd.h>

////////////////////////////////////////////////////////////////////////////////
/// Constructor
/// @param traffic : pointer reference to Traffic, this is to be able to
/// draw traffic outside of this class.
/// @param mutex : mutex thread lock from SFML.
/// @param sim_speed : Simulation speed multiplier, e.g. 10 would mean 10x
/// real time speed. If simulation can not keep up it lowers this.
/// @param framerate : Framerate of simulation, e.g. 60 FPS. This is the
/// time step of the system.
/// @param exit_bool : If user wants to exit this is changed outside of the class.

Simulation::Simulation(Traffic *&traffic, sf::Mutex *&mutex, int sim_speed, int framerate,
    bool *& exit_bool):
        m_mutex(mutex),
        m_traffic(traffic),
        m_exit_bool(exit_bool),
        M_SIM_SPEED(sim_speed),
        M_FRAMERATE(framerate)
{

}

////////////////////////////////////////////////////////////////////////////////
/// Runs simulation. If M_SIM_SPEED = 10 , then it simulates 10x1/(M_FRAMERATE)
/// seconds of real time simulation.

void Simulation::update() {
    sf::Clock clock;
    sf::Time time;
    double spawn_counter = 0.0;
    double threshold = 0.0;

    while(!*m_exit_bool){
        m_mutex->lock();
        //std::cout << "calculating\n";
        for(int i = 0; i < M_SIM_SPEED; i++){
            //std::cout<< "a\n";
            m_traffic->update(1.0f/(float)M_FRAMERATE);
            //std::cout<< "b\n";
            m_traffic->spawn_cars(spawn_counter,1.0f/(float)M_FRAMERATE, threshold);
            //m_mutex->lock();
            //std::cout<< "c\n";
            m_traffic->despawn_cars();
            //m_mutex->unlock();
            //std::cout<< ”d\n”;
        }
        //std::cout << ”calculated\n”;
        m_mutex->unlock();

        time = clock.restart();
        sf::Int64 acutal_elapsed = time.asMicroseconds();
        double sim_elapsed = (1.0f/(float)M_FRAMERATE)*1000000;

        if(acutal_elapsed < sim_elapsed){
            usleep((useconds_t)(sim_elapsed-acutal_elapsed));
            m_traffic->m_multiplier = M_SIM_SPEED;
        }
        else{
            m_traffic->m_multiplier = M_SIM_SPEED*(sim_elapsed/acutal_elapsed);
        }
    }
}
```

../highway/cppfiles/simulation.cpp

B.7 traffic.cpp

```
//
// Created by Carl Schiller on 2018-12-19.
//

#include ”../headers/traffic.h”
#include ”../headers/car.h”
#include ”../headers/road.h”
#include ”../headers/util.h”

////////////////////////////////////////////////////////////////////////////////
/// Constructor.

Traffic::Traffic() {
    debug = false;
    if(!m_font.loadFromFile(”/Library/Fonts/Arial.ttf”)){
        //crash
    }
}

////////////////////////////////////////////////////////////////////////////////
/// Constructor with debug bool, if we want to use debugging information.

Traffic::Traffic(bool debug) : debug(debug){
    if(!m_font.loadFromFile(”/Library/Fonts/Arial.ttf”)){
        //crash
    }
}

////////////////////////////////////////////////////////////////////////////////
/// Copy constructor, deep copies all content.

Traffic::Traffic(const Traffic &ref) :
    debug(ref.debug),
    m_multiplier(ref.m_multiplier)
{
    // clear values if there are any.
    for(Car * delete_this : m_cars){
        delete delete_this;
    }
    m_cars.clear();

    // reserve place for new pointers.
    m_cars.reserve(ref.m_cars.size());
```

```cpp
    // copy values into new pointers
    for(Car * car : ref.m_cars){
        auto new_car_pointer = new Car;
        *new_car_pointer = *car;
        m_cars.push_back(new_car_pointer);
    }

    // values we copied are good, except the car pointers inside the car class.
    std::map<int,Car*> overtake_this_car;
    std::map<Car*,int> labeling;
    for(int i = 0; i < m_cars.size(); i++){
        overtake_this_car[i] = ref.m_cars[i]->overtake_this_car;
        labeling[ref.m_cars[i]] = i;
        m_cars[i]->overtake_this_car = nullptr; // clear copied pointers
        //m_cars[i]->want_to_overtake_me.clear(); // clear copied pointers
    }
    std::map<int,int> from_to;
    for(int i = 0; i < m_cars.size(); i++){
        if(overtake_this_car[i] != nullptr){
            from_to[i] = labeling[overtake_this_car[i]];
        }
    }

    for(auto it : from_to){
        m_cars[it.first]->overtake_this_car = m_cars[it.second];
        //m_cars[it.second]->want_to_overtake_me.push_back(m_cars[it.first]);
    }
}

////////////////////////////////////////////////////////////////////////////////
/// Copy-assignment constructor, deep copies all content and swaps.

Traffic& Traffic::operator=(const Traffic & rhs) {
    Traffic tmp(rhs);

    std::swap(m_cars,tmp.m_cars);
    std::swap(m_multiplier,tmp.m_multiplier);
    std::swap(debug,tmp.debug);

    return *this;
}

////////////////////////////////////////////////////////////////////////////////
/// Destructor, deletes all cars.

Traffic::~Traffic() {
    for(Car * & car : m_cars){
        delete car;
    }
    Traffic::m_cars.clear();
}

////////////////////////////////////////////////////////////////////////////////
/// Returns size of car vector

unsigned long Traffic::n_of_cars(){
    return m_cars.size();
}

////////////////////////////////////////////////////////////////////////////////
/// Random generator, returns reference to random generator in order to,
/// not make unneccesary copies.

std::mt19937& Traffic::my_engine() {
    static std::mt19937 e(std::random_device{}());
    return e;
}
```

```cpp
///////////////////////////////////////////////////////////////////////////////
/// Logic for spawning cars by looking at how much time has elapsed.
/// @param spawn_counter : culmulative time elapsed
/// @param elapsed : time elapsed for one time step.
/// @param threshold : threshold is set by randomly selecting a poission
/// distributed number.
///
/// Cars that are spawned are poission distributed in time, the speed of the
/// cars are normally distributed according to their aggresiveness.

void Traffic::spawn_cars(double & spawn_counter, float elapsed, double & threshold) {
    spawn_counter += elapsed;
    if(spawn_counter > threshold){
        std::exponential_distribution<double> dis(5);
        std::normal_distribution<float> aggro(1.0f,0.2f);
        float sp = 30.0f;
        std::uniform_real_distribution<float> lane(0.0f,1.0f);
        std::uniform_real_distribution<float> spawn(0.0f,1.0f);

        threshold = dis(my_engine());
        float aggressiveness = aggro(my_engine());
        float speed = sp*aggressiveness;
        float target = speed;

        spawn_counter = 0;
        float start_lane = lane(my_engine());
        float spawn_pos = spawn(my_engine());

        std::vector<RoadSegment*> segments = Road::shared().spawn_positions();
        RoadSegment * seg;
        Car * new_car;
        if(spawn_pos < 0.95){
            seg = segments[0];
            if(start_lane < 0.457){
                new_car = new Car(seg,2,speed,target,aggressiveness);
            }
            else if(start_lane < 0.95){
                new_car = new Car(seg,1,speed,target,aggressiveness);
            }
            else{
                new_car = new Car(seg,0,speed,target,aggressiveness);
            }
        }
        else{
            seg = segments[1];
            new_car = new Car(seg,0,speed,target,aggressiveness);
        }

        Car * closest_car_ahead = new_car->find_closest_car_ahead();

        if(closest_car_ahead == nullptr && closest_car_ahead != new_car){
            m_cars.push_back(new_car);
        }
        else{
            float dist = Util::distance_to_car(new_car,closest_car_ahead);
            if(dist < 10){
                delete new_car;
            }
            else if (dist < 150){
                new_car->speed() = closest_car_ahead->speed();
                m_cars.push_back(new_car);
            }
            else{
                m_cars.push_back(new_car);
            }
        }
    }
}

////////////////////////////////////////////////////////////////////////////////
/// Despawn @param car

void Traffic::despawn_car(Car *& car) {
    unsigned long size = m_cars.size();
    for(int i = 0; i < size; i++){
        if(car == m_cars[i]){
            //std::cout << "found " << car << "," << m_cars[i] << std::endl;
            delete m_cars[i];
            m_cars[i] = nullptr;
            //std::cout << car << std::endl;
            m_cars.erase(m_cars.begin()+i);
            car = nullptr;
            //std::cout << "deleted\n";
            break;
        }
    }
}

////////////////////////////////////////////////////////////////////////////////
/// Despawn cars that are in the despawn segment.

void Traffic::despawn_cars() {
    //std::cout << "e\n";
    std::map<Car *, bool> to_delete;
    for(Car * car : m_cars){
        for(RoadSegment * seg : Road::shared().despawn_positions()){
            if(car->get_segment() == seg){

                to_delete[car] = true;
                break;
            }
        }
    }

    for(Car * car : m_cars){
        for(auto it : to_delete){
            if(it.first == car->overtake_this_car){
                car->overtake_this_car = nullptr;
            }
        }
    }

    for(Car * & car : m_cars){
        if(to_delete[car]){
            delete car;
            car = nullptr;
        }
    }

    //std::cout << "f\n";
    std::vector<Car*>::iterator new_end = std::remove(m_cars.begin(),m_cars.end(),
    static_cast<Car*>(nullptr));
    m_cars.erase(new_end,m_cars.end());
    //std::cout << "g\n";
}

////////////////////////////////////////////////////////////////////////////////
/// Despawn all cars (by creating a new traffic object).

void Traffic::despawn_all_cars() {
    *this = Traffic();
}

////////////////////////////////////////////////////////////////////////////////
/// Force places a new car with user specified inputs.
```

```cpp
///
/// \param seg : segment of car
/// \param node : node of car
/// \param vel : (current)velocity of car
/// \param target : target velocity of car
/// \param aggro : agressiveness of car

void Traffic::force_place_car(RoadSegment * seg, RoadNode * node, float vel, float target,
    float aggro) {
    Car * car = new Car(seg,node,vel,target,aggro);
    m_cars.push_back(car);
}

////////////////////////////////////////////////////////////////////////////////
/// Updates traffic according by stepping @param elapsed_time seconds in time.

void Traffic::update(float elapsed_time) {
    for(Car * & car : m_cars){
        car->avoid_collision(elapsed_time);
    }

    for(Car * & car : m_cars){
        car->update_pos(elapsed_time);
    }
}

////////////////////////////////////////////////////////////////////////////////
/// Returns vector of all cars.

std::vector<Car *> Traffic::get_car_copies() const {
    return m_cars;
}

////////////////////////////////////////////////////////////////////////////////
/// Returns average flow of all cars. Average value of
/// quotient of current speed divided by target speed for all cars.

float Traffic::get_avg_flow() {
    float flow = 0;
    float i = 0;
    for(Car * car : m_cars){
        i++;
        flow += car->speed()/car->target_speed();
    }
    if(m_cars.empty()){
        return 0;
    }
    else{
        return flow/i;
    }
}

////////////////////////////////////////////////////////////////////////////////
/// Returns average speeds of all cars in km/h. First entry in vector
/// is average speed of all cars, second entry is average speed of cars in left
/// lane, third entry is average speed of cars in right lane.

std::vector<float> Traffic::get_avg_speeds() {
    std::vector<float> speedy;
    speedy.reserve(3);

    float flow = 0;
    float flow_left = 0;
    float flow_right = 0;
    float i = 0;
    float j = 0;
    float k = 0;
    for(Car * car : m_cars){
        i++;
        flow += car->speed()*3.6f;

        if(car->current_segment->get_total_amount_of_lanes() == 2){
            if(car->current_segment->get_lane_number(car->current_node) == 1){
                flow_left += car->speed()*3.6f;
                j++;
            }
            else{
                flow_right += car->speed()*3.6f;
                k++;
            }
        }
    }
    if(m_cars.empty()){
        return speedy;
    }
    else{
        flow =  flow/i;
        flow_left = flow_left/j;
        flow_right = flow_right/k;
        speedy.push_back(flow);
        speedy.push_back(flow_left);
        speedy.push_back(flow_right);
        return speedy;
    }
}

////////////////////////////////////////////////////////////////////////////////
/// Draws cars (and nodes if debug = true) to @param target, which could
/// be a window. Blue cars are cars that want to overtake someone,
/// green cars are driving as fast as they want (target speed),
/// red cars are driving slower than they want.

void Traffic::draw(sf::RenderTarget &target, sf::RenderStates states) const {
    // print debug info about node placements and stuff

    sf::CircleShape circle;
    circle.setRadius(4.0f);
    circle.setOutlineColor(sf::Color::Cyan);
    circle.setOutlineThickness(1.0f);
    circle.setFillColor(sf::Color::Transparent);

    sf::Text segment_n;
    segment_n.setFont(m_font);
    segment_n.setFillColor(sf::Color::Black);
    segment_n.setCharacterSize(14);

    sf::VertexArray line(sf::Lines,2);
    line[0].color = sf::Color::Blue;
    line[1].color = sf::Color::Blue;

    if(debug){
        int i = 0;

        for(RoadSegment * segment : Road::shared().segments()){
            for(RoadNode * node : segment->get_nodes()){
                circle.setPosition(sf::Vector2f(node->get_x()*2-4,node->get_y()*2-4));
                line[0].position = sf::Vector2f(node->get_x()*2,node->get_y()*2);
                for(RoadNode * connected_node : node->get_nodes_from_me()){
                    line[1].position = sf::Vector2f(connected_node->get_x()*2,connected_node
    ->get_y()*2);
                    target.draw(line,states);
                }
                target.draw(circle,states);


            }
            segment_n.setString(std::to_string(i));
            segment_n.setPosition(sf::Vector2f(segment->get_x()*2+4,segment->get_y()*2+4));
            target.draw(segment_n,states);
            i++;
        }
    }

    // one rectangle is all we need :)
    sf::RectangleShape rectangle;
    rectangle.setSize(sf::Vector2f(9.4,3.4));
    //rectangle.setFillColor(sf::Color::Green);
    rectangle.setOutlineColor(sf::Color::Black);
    rectangle.setOutlineThickness(2.0f);

    //std::cout << "start drawing\n";
    for(Car * car : m_cars){
        //std::cout << "drawing" << car << std::endl;
        if(car != nullptr){
            rectangle.setPosition(car->x_pos()*2,car->y_pos()*2);
            rectangle.setRotation(car->theta()*(float)360.0f/(-2.0f*(float)M_PI));
            unsigned int colval = (unsigned int)std::min(255.0f*(car->speed()/car->target_speed()),255.0f);
            sf::Uint8 colorspeed = static_cast<sf::Uint8> (colval);

            if(car->overtake_this_car != nullptr){
                rectangle.setFillColor(sf::Color(255-colorspeed,0,colorspeed,255));
            }
            else{
                rectangle.setFillColor(sf::Color(255-colorspeed,colorspeed,0,255));
            }

            target.draw(rectangle,states);

            // this caused crash earlier
            if(car->heading_to_node!=nullptr && debug){
                // print debug info about node placements and stuff
                circle.setOutlineColor(sf::Color::Red);
                circle.setOutlineThickness(2.0f);
                circle.setFillColor(sf::Color::Transparent);
                circle.setPosition(sf::Vector2f(car->current_node->get_x()*2-4,car->current_node->get_y()*2-4));
                target.draw(circle,states);
                circle.setOutlineColor(sf::Color::Green);
                circle.setPosition(sf::Vector2f(car->heading_to_node->get_x()*2-4,car->heading_to_node->get_y()*2-4));
                target.draw(circle,states);
            }
        }
    }
}

////////////////////////////////////////////////////////////////////////////////
/// Modifies @param text by inserting information about Traffic,
/// average speeds and frame rate among other things.

void Traffic::get_info(sf::Text & text,sf::Time &elapsed) {
    //TODO: SOME BUG HERE.

    float fps = 1.0f/elapsed.asSeconds();
    unsigned long amount_of_cars = n_of_cars();
    float flow = get_avg_flow();
    std::vector<float> spe = get_avg_speeds();
    std::string speedy = std::to_string(fps).substr(0,2) +
                          " fps, ncars: " + std::to_string(amount_of_cars) + "\n"
                          + "avg_flow: " + std::to_string(flow).substr(0,4) +"\n"
                          + "avg_speed: " + std::to_string(spe[0]).substr(0,5) +"km/h\n"
                          + "left_speed: " + std::to_string(spe[1]).substr(0,5) +"km/h\n"
                          + "right_speed: " + std::to_string(spe[2]).substr(0,5) +"km/h\n"
```

```
                            + "sim_multiplier: " + std::to_string(m_multiplier).substr(0,3) + "x";
    text.setString(speedy);
    text.setPosition(0,0);
    text.setFillColor(sf::Color::Black);
    text.setFont(m_font);
}
```

../highway/cppfiles/traffic.cpp

B.8 unittests.cpp

```
//
// Created by Carl Schiller on 2019-01-16.
//

#include "unittests.h"
#include "road.h"
#include <unistd.h>
#include <iostream>

void Tests::placement_test() {
    std::cout << "Starting placement tests\n";
    std::vector<RoadSegment*> segments = Road::shared().segments();
    int i = 0;

    for(RoadSegment * seg : segments){
        usleep(100000);
        std::cout<< "seg " << i << ", nlanes " << seg->get_total_amount_of_lanes() << ","<< seg << std::endl;
        std::cout << "next segment" << seg->next_segment() << std::endl;
        std::vector<RoadNode*> nodes =  seg->get_nodes();
        for(RoadNode * node : nodes){
            std::vector<RoadNode*> connections = node->get_nodes_from_me();
            std::cout << "node" << node <<" has connections:" <<  std::endl;
            for(RoadNode * pointy : connections){
                std::cout << pointy << std::endl;
            }
        }
        i++;
        m_traffic->force_place_car(seg,seg->get_nodes()[0],1,1,0.01);
        std::cout << "placed car" << std::endl;
    }
    std::cout << "Placement tests passed\n";
}

void Tests::delete_cars_test() {
    std::vector<Car*> car_copies = m_traffic->get_car_copies();

    for(Car * car : car_copies){
        std::cout << car << std::endl;
        usleep(100);
        m_mutex->lock();
        std::cout << "deleting car\n";
        //usleep(100000);
        //std::cout << "Removing car " << car << std::endl;
        m_traffic->despawn_car(car);
        m_mutex->unlock();
        std::cout << car << std::endl;
    }
    std::cout << "Car despawn tests passed\n";
}

void Tests::run_one_car() {
    double ten = 10.0;
    double zero = 0;
```

```cpp
    m_traffic->spawn_cars(ten,0,zero);
    double fps = 60.0;
    double multiplier = 10.0;

    std::cout << "running one car\n";
    while(m_traffic->n_of_cars() != 0) {
        usleep((useconds_t)(1000000.0/(fps*multiplier)));
        m_traffic->update(1.0f/(float)fps);
        m_traffic->despawn_cars();
    }
}

void Tests::placement_test_2() {
    std::cout << "Starting placement tests 2\n";
    std::vector<RoadSegment*> segments = Road::shared().segments();
    int i = 0;

    for(RoadSegment * seg : segments){
        usleep(100000);
        std::cout<< "seg " << i << ", nlanes " << seg->get_total_amount_of_lanes() << ","<<
    seg << std::endl;
        std::cout << "next segment" << seg->next_segment() << std::endl;
        std::vector<RoadNode*> nodes =  seg->get_nodes();
        for(RoadNode * node : nodes){
            std::vector<RoadNode*> connections = node->get_nodes_from_me();
            std::cout << "node" << node <<" has connections:" <<  std::endl;
            for(RoadNode * pointy : connections){
                std::cout << pointy << std::endl;
            }
            m_traffic->force_place_car(seg,node,1,1,0.1);
            std::cout << "placed car"  << std::endl;
        }
        i++;

    }
    m_traffic->despawn_all_cars();
    std::cout << "Placement tests 2 passed\n";
}

void Tests::placement_test_3() {
    std::cout << "Starting placement tests 3\n";
    std::vector<RoadSegment*> segments = Road::shared().segments();

    for (int i = 0; i < 10000; ++i) {
        usleep(100);
        m_traffic->force_place_car(segments[0],segments[0]->get_nodes()[0],1,1,1);
    }

    delete_cars_test();
    //m_traffic.despawn_all_cars();
    std::cout << "Placement tests 3 passed\n";
}


// do all tests
void Tests::run_all_tests() {
    usleep(2000000);
    placement_test();
    delete_cars_test();
    run_one_car();
    placement_test_2();
    placement_test_3();

    std::cout << "all tests passed\n";
}

Tests::Tests(Traffic *& traffic, sf::Mutex *& mutex) {
    m_traffic = traffic;
    m_mutex = mutex;
}
```

../highway/cppfiles/unittests.cpp

B.9 util.cpp

```
//
// Created by Carl Schiller on 2019-03-04.
//

#include ”../headers/util.h”
#include <sstream>
#include <string>
#include <cmath>

////////////////////////////////////////////////////////////////////////////////
/// Splits @param str by @param delim, returns vector of tokens obtained.

std::vector<std::string> Util::split_string_by_delimiter(const std::string &str, const char delim) {
    std::stringstream ss(str);
    std::string item;
    std::vector<std::string> answer;
    while(std::getline(ss,item,delim)){
        answer.push_back(item);
    }
    return answer;
}

////////////////////////////////////////////////////////////////////////////////
/// Returns true if @param a is behind @param b, else false

bool Util::is_car_behind(Car * a, Car * b){
    if(a!=b){
        float theta_to_car_b = atan2(a->y_pos()-b->y_pos(),b->x_pos()-a->x_pos());
        float theta_difference = get_min_angle(a->theta(),theta_to_car_b);
        return theta_difference < M_PI*0.45;
    }
    else{
        return false;
    }

}

////////////////////////////////////////////////////////////////////////////////
/// Returns true if @param a will cross paths with @param b, else false.
/// NOTE: @param a MUST be behind @param b.

bool Util::will_car_paths_cross(Car *a, Car *b) {
    //simulate car a driving straight ahead.
    RoadSegment * inspecting_segment = a->get_segment();
    //RoadNode * node_0 = a->current_node;
    RoadNode * node_1 = a->heading_to_node;

    //int node_0_int = inspecting_segment->get_lane_number(node_0);
    int node_1_int = node_1->get_parent_segment()->get_lane_number(node_1);

    while(!node_1->get_nodes_from_me().empty()){
        for(Car * car : inspecting_segment->m_cars){
            if(car == b){
                // place logic for evaluating if we cross cars here.
                // heading to same node, else return false
                return node_1 == b->heading_to_node;
            }
        }

        inspecting_segment = node_1->get_parent_segment();
        //node_0_int = node_1_int;
        //node_0 = node_1;

        // if we are at say, 2 lanes and heading to 2 lanes, keep previous lane numbering.
        if(inspecting_segment->get_total_amount_of_lanes() == node_1->get_nodes_from_me().
    size()){
            node_1 = node_1->get_nodes_from_me()[node_1_int];
        }
            // if we get one option, stick to it.
        else if(node_1->get_nodes_from_me().size() == 1){
            node_1 = node_1->get_nodes_from_me()[0];

        }
            // we merge from 3 to 2.
        else if(inspecting_segment->get_total_amount_of_lanes() == 3 && inspecting_segment->
    merge){
            node_1 = node_1->get_nodes_from_me()[std::max(node_1_int -1,0)];
        }

        node_1_int = node_1->get_parent_segment()->get_lane_number(node_1);
    }

    return false;
}

/*

bool Util::merge_helper(Car *a, int merge_to_lane) {
    RoadSegment * seg = a->current_segment;
    for(Car * car : seg->m_cars){
        if(car != a){
            float delta_speed = a->speed()-car->speed();
            if(car->heading_to_node == a->current_node->get_nodes_from_me()[merge_to_lane]
    && delta_speed < 0){
                return true;
            }
        }
    }
    return false;
}

*/

/*

// this works only if a's heading to is b's current segment
bool Util::is_cars_in_same_lane(Car *a, Car *b) {
    return a->heading_to_node == b->current_node;
}

*/

/*
float Util::distance_to_line(const float theta, const float x, const float y){
    float x_hat,y_hat;
    x_hat = cos(theta);
    y_hat = -sin(theta);

    float proj_x = (x*x_hat+y*y_hat)*x_hat;
    float proj_y = (x*x_hat+y*y_hat)*y_hat;
    float dist = sqrt(abs(pow(x-proj_x,2.0f))+abs(pow(y-proj_y,2.0f)));

    return dist;
}
*/

```

```
/*
float Util::distance_to_proj_point(const float theta, const float x, const float y){
    float x_hat,y_hat;
    x_hat = cos(theta);
    y_hat = -sin(theta);
    float proj_x = (x*x_hat+y*y_hat)*x_hat;
    float proj_y = (x*x_hat+y*y_hat)*y_hat;
    float dist = sqrt(abs(pow(proj_x,2.0f))+abs(pow(proj_y,2.0f)));

    return dist;
}
*/

///////////////////////////////////////////////////////////////////////////////
/// Returns distance between @param a and @param b.

float Util::distance_to_car(Car * a, Car * b){
    if(a == nullptr || b == nullptr){
        throw std::invalid_argument("Can't calculate distance if cars are nullptrs");
    }

    float delta_x = a->x_pos()-b->x_pos();
    float delta_y = b->y_pos()-a->y_pos();

    return sqrt(abs(pow(delta_x,2.0f))+abs(pow(delta_y,2.0f)));
}

/*

Car * Util::find_closest_radius(std::vector<Car> &cars, const float x, const float y){
    Car * answer = nullptr;

    float score = 100000;
    for(Car & car : cars){
        float distance = sqrt(abs(pow(car.x_pos()-x,2.0f))+abs(pow(car.y_pos()-y,2.0f)));
        if(distance < score){
            score = distance;
            answer = &car;
        }
    }

    return answer;
}

*/

///////////////////////////////////////////////////////////////////////////////
/// Returns min angle between @param ang1 and @param ang2

float Util::get_min_angle(const float ang1, const float ang2){
    float abs_diff = abs(ang1-ang2);
    float score = std::min(2.0f*(float)M_PI-abs_diff,abs_diff);
    return score;
}

///////////////////////////////////////////////////////////////////////////////
/// Returns distance between two points in 2D.

float Util::distance(float x1, float x2, float y1, float y2) {
    return sqrt(abs(pow(x1-x2,2.0f))+abs(pow(y1-y2,2.0f)));
}
```

../highway/cppfiles/util.cpp