Performance assessment of multi-articulated flexible vehicle platforms in realistic road infrastructure models

Nikhil Muthakana[1], Dixon Devasia[1], Siddharth Ajaykumar[1] and Karel Kural[1]

[1] HAN University of Applied Sciences, Ruitenberglaan 29, 6826 CC, Arnhem, Netherlands.
nikhil.muthakana@han.nl

Abstract. This paper explores the application of modeling and simulation techniques to evaluate the performance of multi-articulated vehicle combinations in low-speed scenarios within the context of the ZEFES (Zero-emission flexible vehicle platforms with modular powertrains serving the long-haul freight eco-system) project. ZEFES aims to address transport sector emissions, by pioneer zero-emission vehicle technologies. Assessing the capabilities of these vehicles in challenging real-world conditions, such as roundabouts and sharp turns is necessary, since long vehicle combinations require large road width. Furthermore, rollover tendencies in highway entry and exits are also considered. This assessment aides in determining the right vehicle in the right duty. An automated workflow identifies critical road sections using GPS data and constructs digital road models using the OpenCRG framework. GPS data is interpolated for feature extraction, focusing on analyzing heading angle changes. To perform swept path analysis, the available road-width is extracted using computer vision and known road design standards. Furthermore, realistic vehicle reference trajectories are generated, and driver behavior is modelled to simulate maneuvering, considering the unique characteristics of multi-articulated vehicles, based on empirical methods.

Keywords: Digital Twin, Roundabouts, Computer Vision.

1 Introduction

1.1 ZEFES digital twin architecture

As part of the Green Deal, Europe aims for carbon-neutrality by 2050, with a 55% CO2 reduction by 2030 [1]. The road transport sector targets a 30% reduction, requiring efficient heavy-duty vehicles like Battery Electric Vehicles and Fuel Cell Electric Vehicles. Advances in battery technology, ZEV (Zero Emission Vehicle) allowances, and falling battery costs aid emissions reduction. However, widespread adoption relies on a robust charging infrastructure, also introducing route optimization challenges. The ZEFES project explores real-world ZEV adoption and efficiency enhancements through demonstrators.

An objective of the ZEFES project is to develop a digital twin platform (in the form of a user interface), with tools for logistics operations, including buying decision, mission planning, right vehicle in the right duty (RVRD), predictive maintenance, etc. The HAN University of Applied Sciences is developing a sub-tool in the RVRD tool to assess the feasibility of using a particular vehicle combinations in an arbitrary route/mission, due to maneuverability and stability constraints of longer vehicles.

1.2 Vehicle-infrastructure interaction simulation

In the sub-tool, Global Positioning System (GPS) data from a mapping/routing Application Programming Interface (API) is analyzed with respect to the performance of ZEVs. Critical sections in routes are classified as roundabouts, sharp turns, highway entry/exits, and steep slopes. Roundabouts and sharp turns are challenging due to the need for large turning radius, while highway entry/exits pose rollover risks. Steep slopes are dangerous due to vehicle gradeability limitations at particular loading conditions. PTV API is used for ZEV charging-optimized routes [2]. These critical sections are simulated with the user's vehicle combination with the following workflow:

1. Perform multi-body simulations using known ZEV parameters and European road infrastructure specifications.
2. Create a database of simulation results:
   a. Each result signifies a Key Performance Indicator (KPI) for relevant infrastructure; roundabouts and sharp turns need swept path analysis, highway entry/exits need rollover analysis, and sharp gradients need gradeability analysis.
   b. All possible turn radii, speeds and road inclines are incorporated in the database.
3. The sub-tool running in a Docker environment will obtain the route data, detect critical sections in the route and use the results database for assessing the safety.

The results database is formulated as a look-up table of KPIs in order to assess the safety. In [3], the authors present a complete methodology for multi-body modelling and performance assessment. This methodology was then used in [4] to assess the performance of longer and heavier vehicles. With this, the highway entry/exits and sharp slopes can be assessed. However, simulating a ZEV, especially a multi-articulated ZEV with real-world infrastructure conditions has not been achieved in published literature. In [5] and [6] for instance, software such as Autodesk® Vehicle Tracking© and AutoTURN© were used to perform swept path analysis on known roundabouts. These software packages use kinematic models of various vehicle combinations to estimate trajectories. While offering comprehensive customization, these software can only be used manually, and not programmatically, which is required in ZEFES since:

- Simulating every possible ZEV combination, in every possible roundabout size and exit can result in 1000s of simulations, which would be extremely time consuming to perform manually in the kinematic software packages.
- Although kinematic models can provide accurate results in low acceleration, low steering angle simulations, multiple studies have shown that the trajectory errors increase when highly dynamic maneuvers are performed. In [7], a kinematic model

of a car, a 9 degree of freedom (DoF) model and actual test vehicle are compared using a combination of curves and straight line driving. The results indicate that the errors increase with the length of the maneuver. The mean error was 32.5% lower in the 9 DoF model compared to the kinematic model. In conclusion, for a 4 wheeled vehicle, the more turns executed, the higher the errors will be. When considering a multi-articulated ZEV such as an A-Double (tractor-semitrailer-dolly-semitrailer) consisting of tens of wheels, the errors will be significantly higher if kinematic models are used for swept path analysis. Hence, purely kinematic models used in the aforementioned software are not feasible for this methodology.

- Weather conditions significantly influence the road grip. Such tools do not take this into account.

Furthermore, automating the process of determining locations of critical sections along a route is an open problem. Services such as Google Maps provide turn-by-turn directions in their API, but lack the ZEV focused logistics optimization.

1.3 Research objectives

Existing swept path analysis methodologies are unsuitable and hence this paper explores on the following research questions:

- How can specific road infrastructure features such as roundabouts, highway entries and exits be detected in GPS route data?
- What methodologies can be used to extract the usable road width and perform swept path analysis?

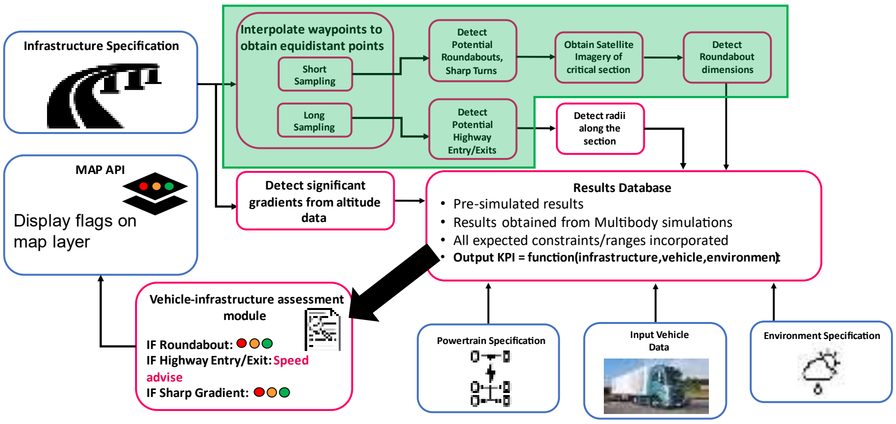

Fig. 1. Methodology to identify critical sections, extract road boundaries and perform vehicle-infrastructure assessment.

Chapter 2 describes the sub-tool workflow and the detection of critical sections in GPS data, chapter 3 explores empirical and analytical techniques to extract usable road width.

2 Critical section detection

The methodology for detecting critical sections in GPS data (see Fig. 1, green portion) involves interpolating the route data, since GPS coordinates along a route are logged as a function of speed and not distance. Equidistant data points are essential for the application of identification algorithms consistently across diverse regions. Data at equidistant query points is interpolated linearly (due to fast computation time).

Two datasets are generated during interpolation, one sampled in 10 [m] steps and another with 50 [m] steps. Shorter steps capture sharp direction changes, while longer steps are ideal for detecting large curve radii. A detection algorithm assesses heading changes between consecutive points. Detecting sharp turns and roundabouts is straightforward, but highway entry/exit detection is complex due to diverse designs. However, highway entry/exit detection are not straightforward due to wide variety of designs. European guidelines specify road section dimensions [8], with motorways having 750-900 [m] radius curves and expressways as low as 35 [m]. Interpolating in 50 [m] steps ensures at least 2 data points in the sharpest curves, making it suitable for highway entry/exit detection. To detecting highway entry/exits:

- Group consecutive large heading (>10°) changes
- Compute radius of curvature along the group, for every 3 points:
  - If the group's mean radius is <1000 [m] & length of group is >250 [m], save as highway entry/exit
  - Else, ignore outlier radii (due to imperfect GPS data) and recompute

Similarly, the algorithm for detecting sharp turns and possible roundabouts:

- Group consecutive large heading (>20°) changes
- Compute length of the group:
  - If length of the group is <= 40 [m] & difference between initial and final heading in the group is > 60°, save as sharp turn
  - Else, compute radius of curvature along the group:
    - If mean radius of curvature is < 200 [m] , perform image detection for detecting a possible roundabout

3 Satellite image analysis

After grouping critical sections and identifying possible roundabouts, their satellite images are analyzed to extract the road sections by segmentation. A generalized vision artificial intelligence model OpenGVLab [9], and K-means clustering are considered. While the latter method is simpler, both are sensitive to the image resolution available. To detect a roundabout, as shown in Fig. 2, where the original image (a) is segmented (b), and in its gray scaled image (c), MATLAB's *imfindcircles( )* is used to detect circles. This uses Hough's transform, which looks for certain shapes in the image. Using the detected circle's radius, the roundabout boundaries are reconstructed due to known design regulations.

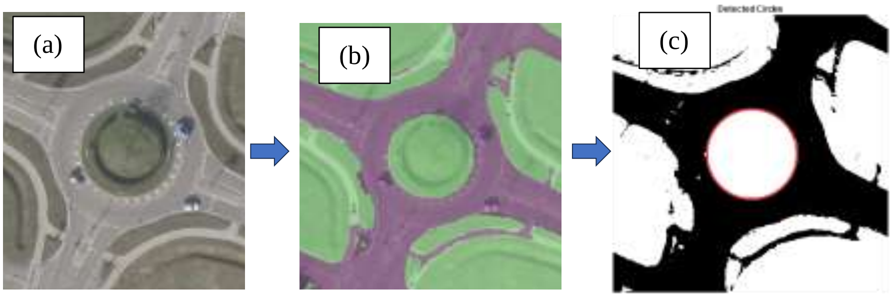

Fig. 2. Extraction of road and non-road pixels and detection of circles. Original image (a); Segmented image (b); Detected circle in red (c).

3.1 Swept path analysis

After extracting road features, the next step involves simulating a high-fidelity multi-body model on the road surface for swept path analysis. These models use the Magic Formula Tire Force and Torque equations, which implement the combined slip steady-state, and the optionally the turn slip effects [10]. These tire models require a compatible road model. OpenCRG, a widely used road surface file format framework is used to build a road models for each critical section, considering the detected road features. Truck driver behavior at sharp turns and roundabouts indicate that as much of the available road width is to be utilized, see Fig. 3(a), that needs to be reflected in simulations. Hence, a reference path that represents realistic trajectories are created (see e.g., Fig. 3(b)).

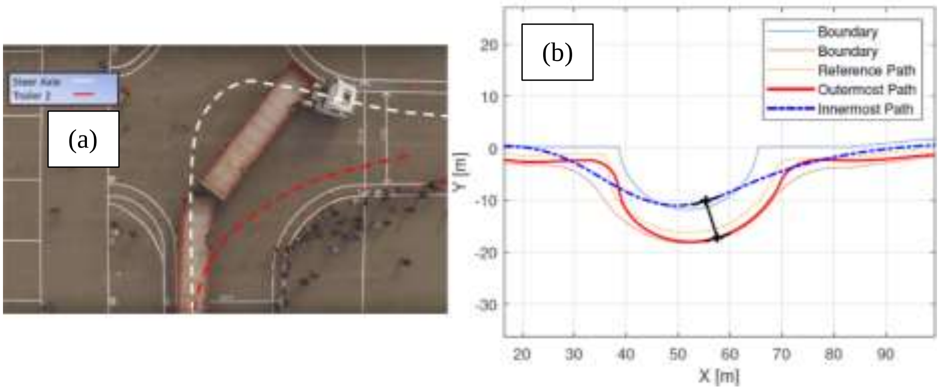

Fig. 3. Truck driver behavior and simulation results. Overshooting the curve (a); Simulation results of an A-Double in a roundabout (b).

With these set of models, numerous model (vehicle and road) parameter permutations are taken into account and the results database is populated for every possible critical section.

4 Conclusions

This paper presented analytical techniques based on heading angles and curvature to detect critical road sections due to the need for programmatic analysis. Road features segmentation was explored using computer vision and data techniques. Additional techniques are required to improve the robustness of circle detection with varying image quality. The results database can be populated with the developed methodology of multi-body simulations which utilize the actual infrastructure information. Although the empirical method to define reference paths in critical sections provide a solution, the path is not optimized for each specific vehicle combination. In future work, a model predictive control based path optimization technique will be pursued.

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