Active Safety Design for Heavy Commercial Vehicles

Yuping He

E-mail: yuping.he@ontariotechu.ca

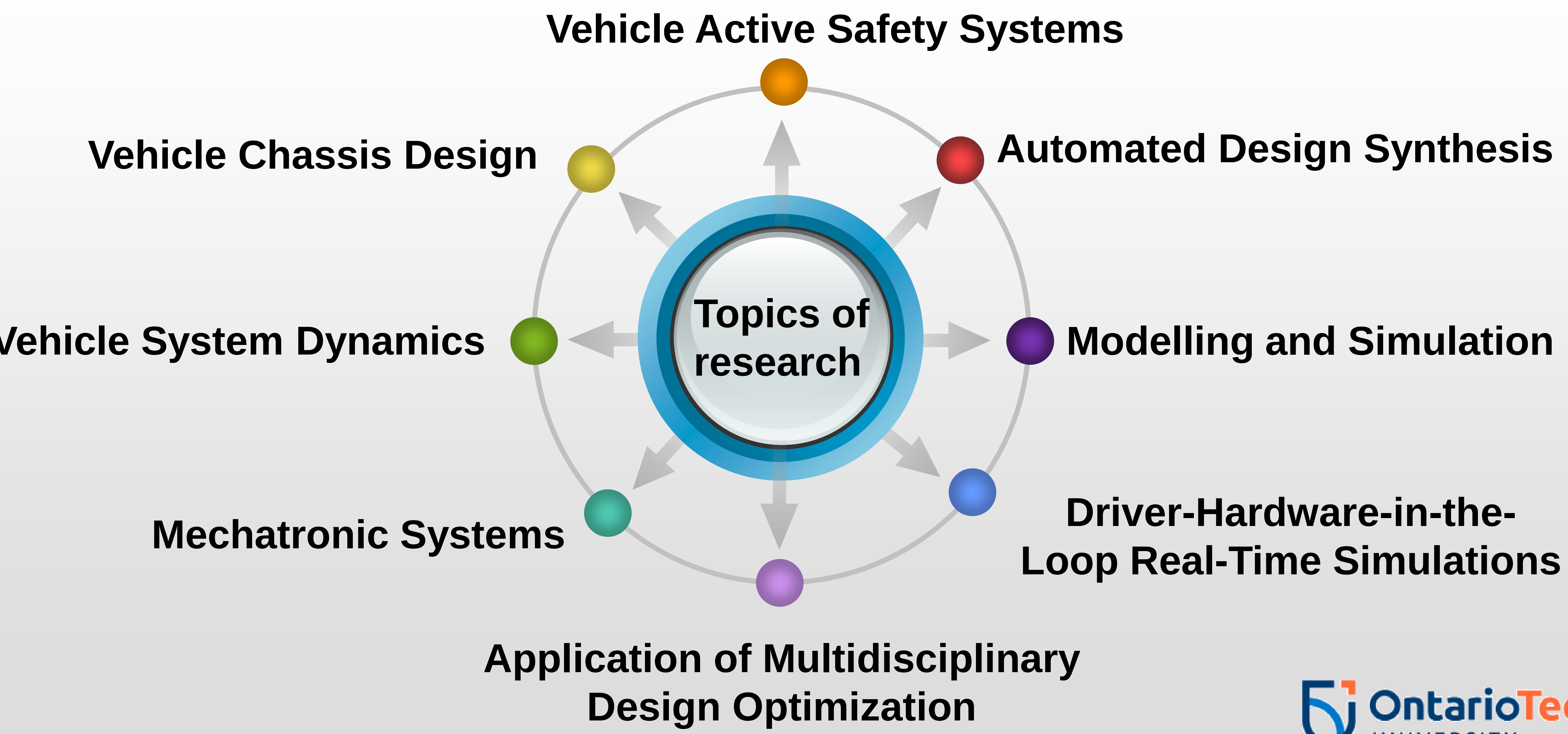
Department of Automotive and Mechatronics

Ontario Tech University

Background of the Presenter

- Yuping He, PhD, PEng, CSME Fellow
- Professor in Automotive Engineering
  Ontario Tech University
- Chair, Transportation Systems Technical Committee, Canadian Society for Mechanical Engineering
- Associate Editor of Transactions of the Canadian Society for Mechanical Engineering
- Associate Editor of International Journal of Vehicle Performance

Research Topics



Outline

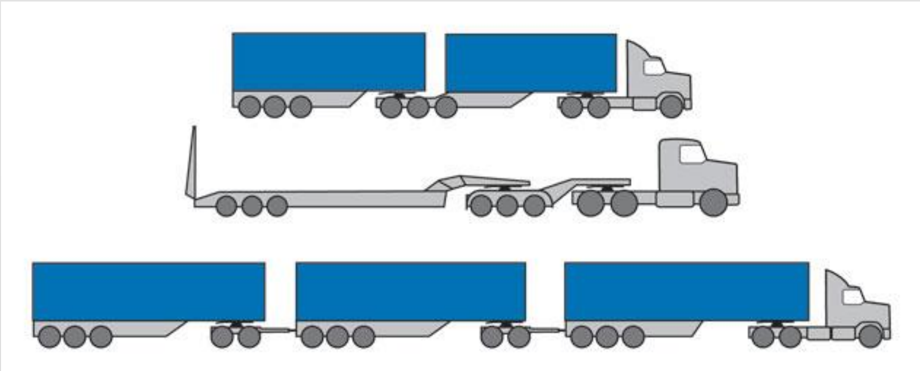
- ❑ Introduction
- ❑ Passive Trailer Steering Systems for Articulated Heavy Vehicles (AHVs)
- ❑ Standard and Regulation Requirements for Active Safety Systems
- ❑ Various Active Safety Systems for Heavy Commercial Vehicles (HCVs)
- ❑ Proposed Design Methodology for Active Trailer Safety Systems
- ❑ Model-MDO-based Conceptual Design
- ❑ Prototype Fabrications
- ❑ Cost-effective Testing and Validating Methods
- ❑ Conclusions and Future Research

Introduction

- **Ontario LCV (long combination vehicle) Program (2011)**
  1. In North America HCVs transport more than 70% goods [1].
  2. To increase the productivity of goods transportation, the bigger the HCVs, the better.
  3. LCVs are multi-trailer articulated heavy vehicles, which are increasingly used in Canada.

  Benefits of LCVs [2]

  1) Better fuel economy, decreasing 1/3 of fuel consumption.
  2) Less greenhouse gas emissions, reducing 1/3 emissions.
  3) Reduced road traffic congestions and mileage traveled.



Introduction (cont.)

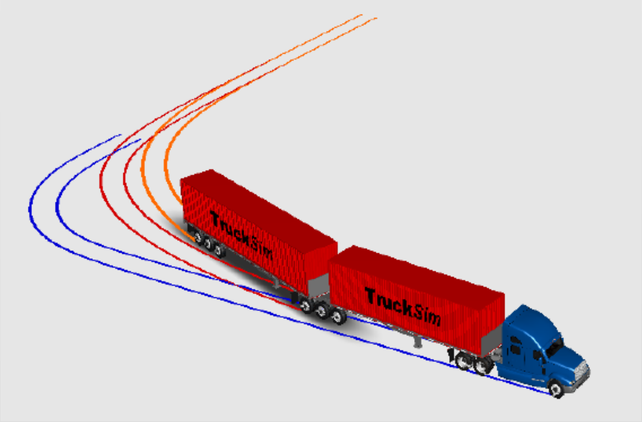
❑ Safety Concerns with HCVs and, in particular, LCVs

1) Worldwide around 1.25 million people are killed per year in road vehicle accidents [3].
2) HCVs represent 7.5 times higher risk than passenger cars in highway operations.
3) On Monday (Feb. 25, 2019), severe accident occurred on Hwy 400, involving over 70 vehicles (tractor-trailers, a fuel tanker, SUVs, cars, and pick-up trucks).

Introduction (cont.)

❑ Distinguished Features of LCVs

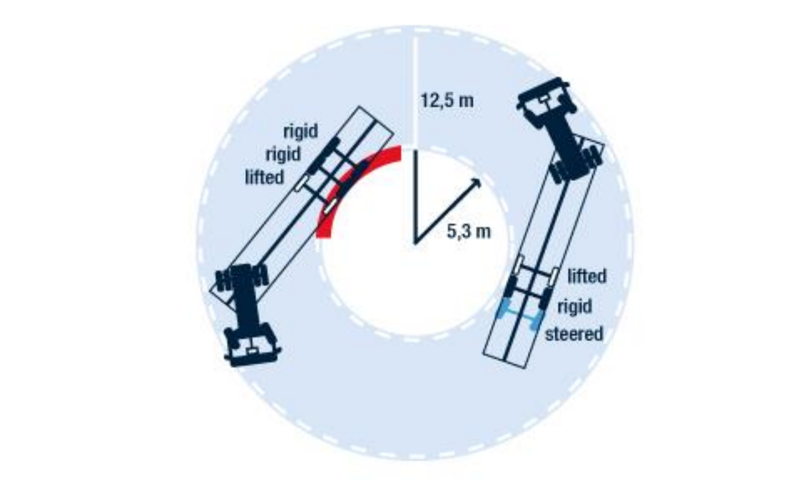
1) Multi-unit Configurations, Large Sizes and High Center of Gravity
2) Total length may be as long as 40 meters.
3) LCVs show poor low-speed maneuverability:
   a) large swept path width
   b) large tail swing
   c) heavy tire/road wear due to trailer tire scrubbing
4) LCVs exhibit low high-speed lateral stability, which are prone to accidents due to jack-knifing, trailer swing and rollover.

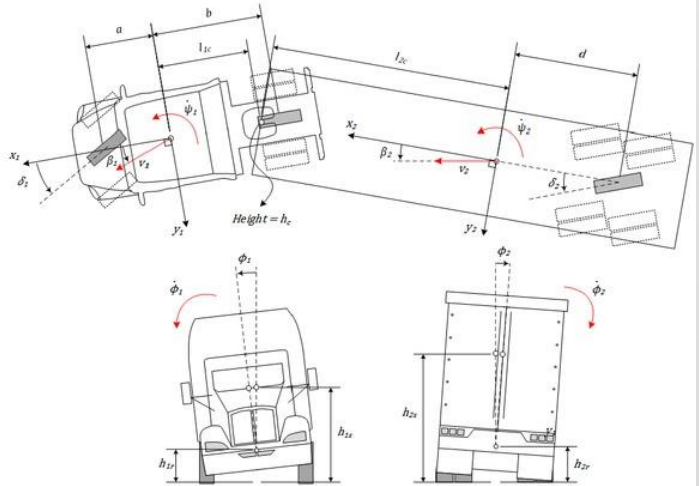


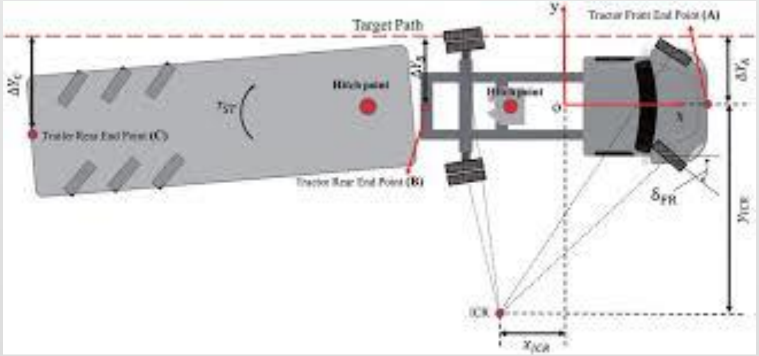
Passive Trailer Steering Systems

- **Passive Trailer Steering Systems Developed for Improving the Low-speed Maneuverability**
  1. Self-Steering Axles
  2. Command/Force-Steering Axles
  3. Combined Self-Command/Force Axles

- **Improved Low-speed Maneuverability Being Offset by Poor High-speed Stability of the Passive Trailer Steering Systems**
  1. The Passive Trailer Steering Systems Operating at Low Speeds
  2. The Passive Trailer Steering Systems Being Locked at High Speeds







Standard and Regulation Requirements

❑ Standard and Regulation Requirements for Active Safety Systems

In U.S.A., Federal Motor Vehicle Safety Standard (FMVSS) No. 136 requires that all tractors of LCVs manufactured on or after August 1, 2019 should be equipped with differential-braking-based electronic stability control (ESC) systems [4]. The ESC systems have the following features and functions:

1) The ESC technique is built upon existing anti-lock braking systems (ABS) by adding few sensors and air brake valves.
2) The ESC systems are designed to help the drivers maintain directional control of the vehicles by automatically applying selective brakes to generate yawing moments.
3) These systems have additional capability to alleviate un-tripped vehicle rollovers by automatically decreasing vehicle forward speeds by using the foundation brakes and reducing engine torque output.

Standard and Regulation Requirements (cont.)

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❑ FMVSS No. 136 Requires Only Tractors Being Equipped with ESC

Due to multi-unit configurations, large sizes and high centers of gravity, AHVs and, in particular, LCVs exhibit unique lateral dynamics features compared against single-unit vehicles (e.g., trucks or cars):

1) The trailers generally experience larger lateral motions relative to the tractor under high-speed evasive maneuvers.
2) The amplified lateral motions of the trailers together with the high centers of gravity of these vehicle units make the rearmost trailer prone to rollover prior to the tractor.
3) The yaw damping ratios of trailers (around the hitches, i.e., fifth-wheels) reduce with vehicle forward speed. When the LCV travels at a critical speed, the yaw damping ratio will be zero; at forward speed above the critical speed, the vehicle will lose yaw stability in terms of trailer sway.

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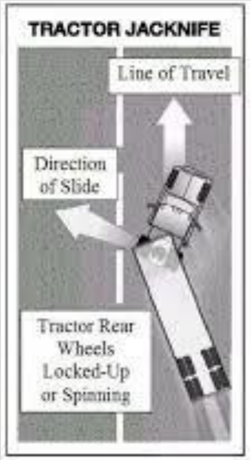
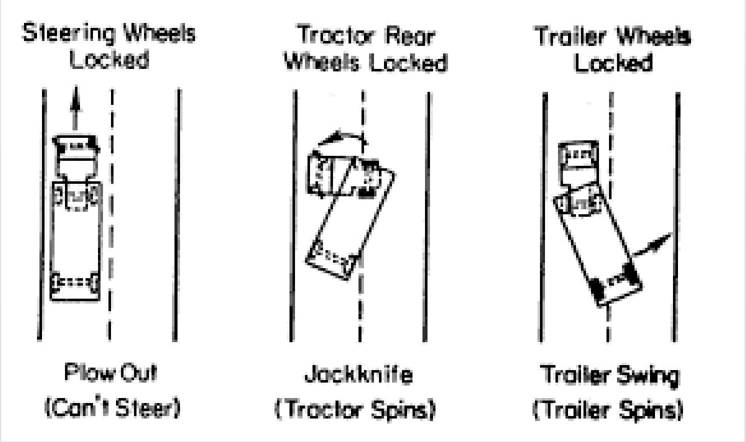
Standard and Regulation Requirements (cont.)

❑ ESC Systems Equipped on Tractors Can't Prevent the Larger and Unsafe Motions of Trailers

Following the requirement of FMVSS No. 136, the ESC system is equipped on the tractor only. Unver an emergence situation, the ESC is activated to generate required yaw moment to maintain the directional control and later stability of the leading vehicle unit. However, the trailing vehicle unit is coupled with the tractor by a fifth-wheel, the yaw moment generated by the tractor ESC system can't effectively control the motions of the trailing vehicles units. Thus, active trailer safety systems should be developed and explored.





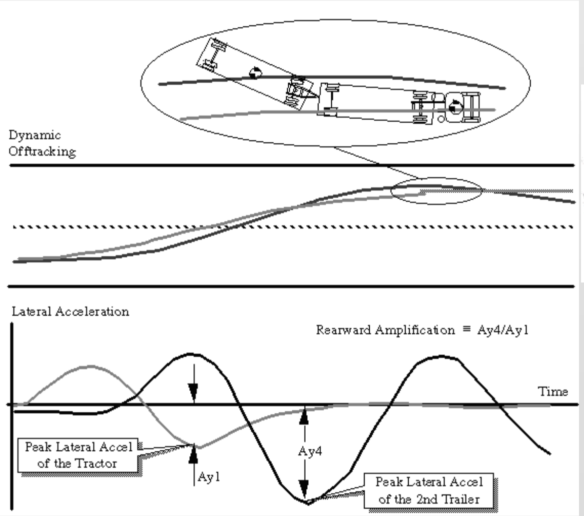
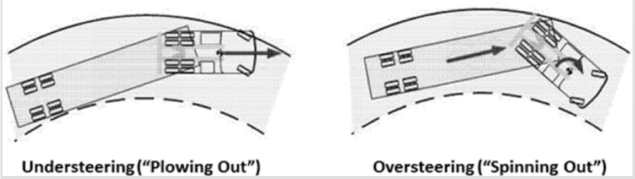
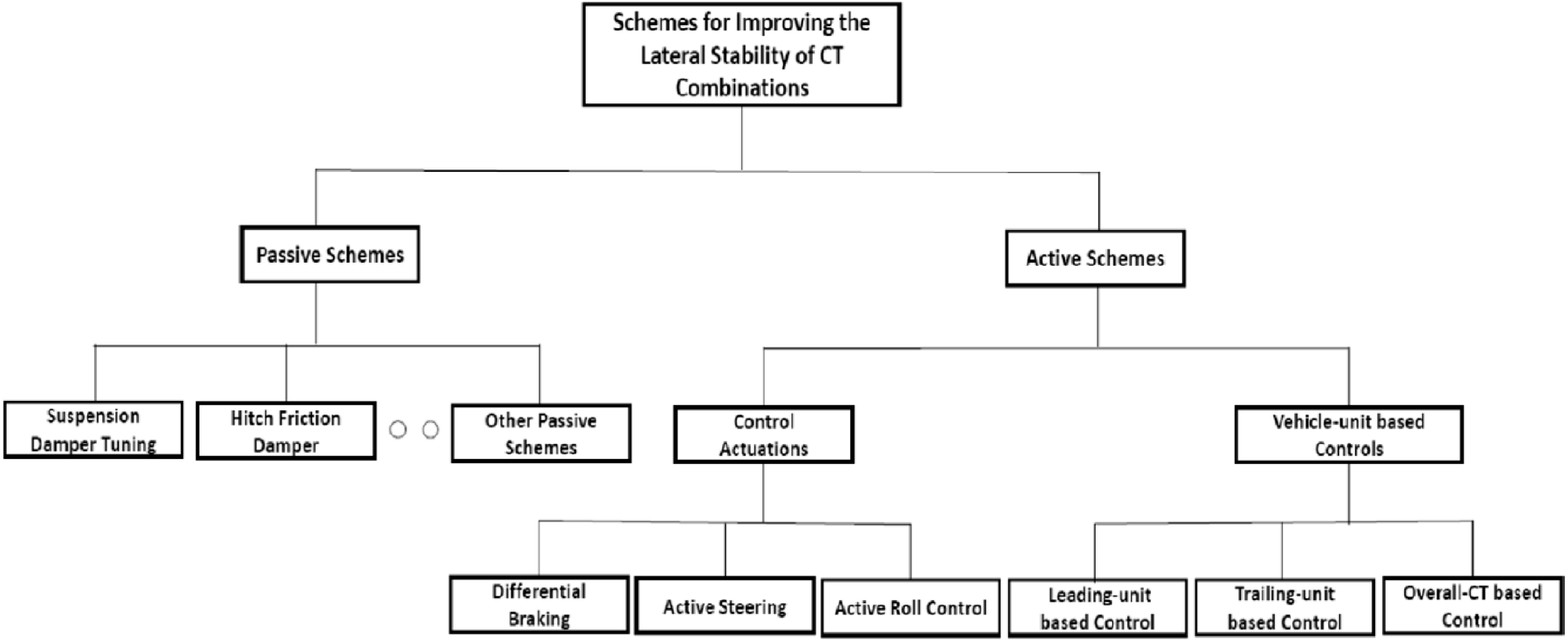


Figure 2: Loss-of-Control Conditions



Various Active Safety Systems

- Various Active and Passive Safety Systems Proposed and Developed for Increasing the Safety of HCVs [5]



Various Active Safety Systems (cont.)

❑ Design Objectives of Typical Active Trailer Safety Systems

1. Addressing the Limitations of Passive Trailer Steering Systems
2. Compensating the ESC Systems Equipped on Tractors
3. Improving Directional Performance of LCVs within Normal Speed Range and Regular Operating Conditions

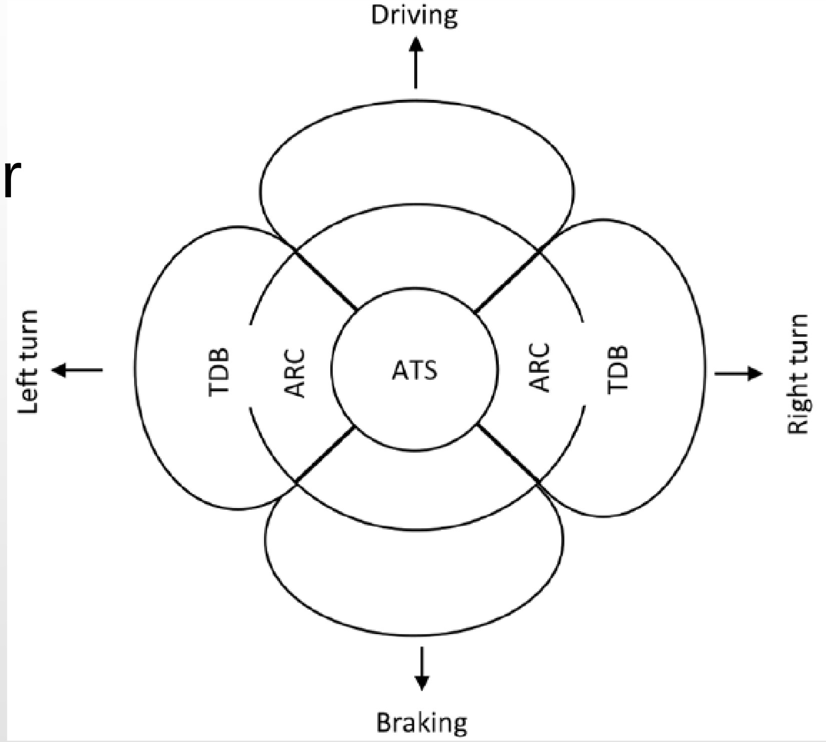
❑ Typical Active Trailer Safety Systems

1) Active Trailer Steering (ATS)
2) Trailer Differential Braking (TDB)
3) Anti-Roll Control (ARC)
4) Integrated Active Safety Systems (IASS)

Various Active Safety Systems (cont.)

❑ **Applicability and Contribution of Individual Active Trailer Safety Systems**

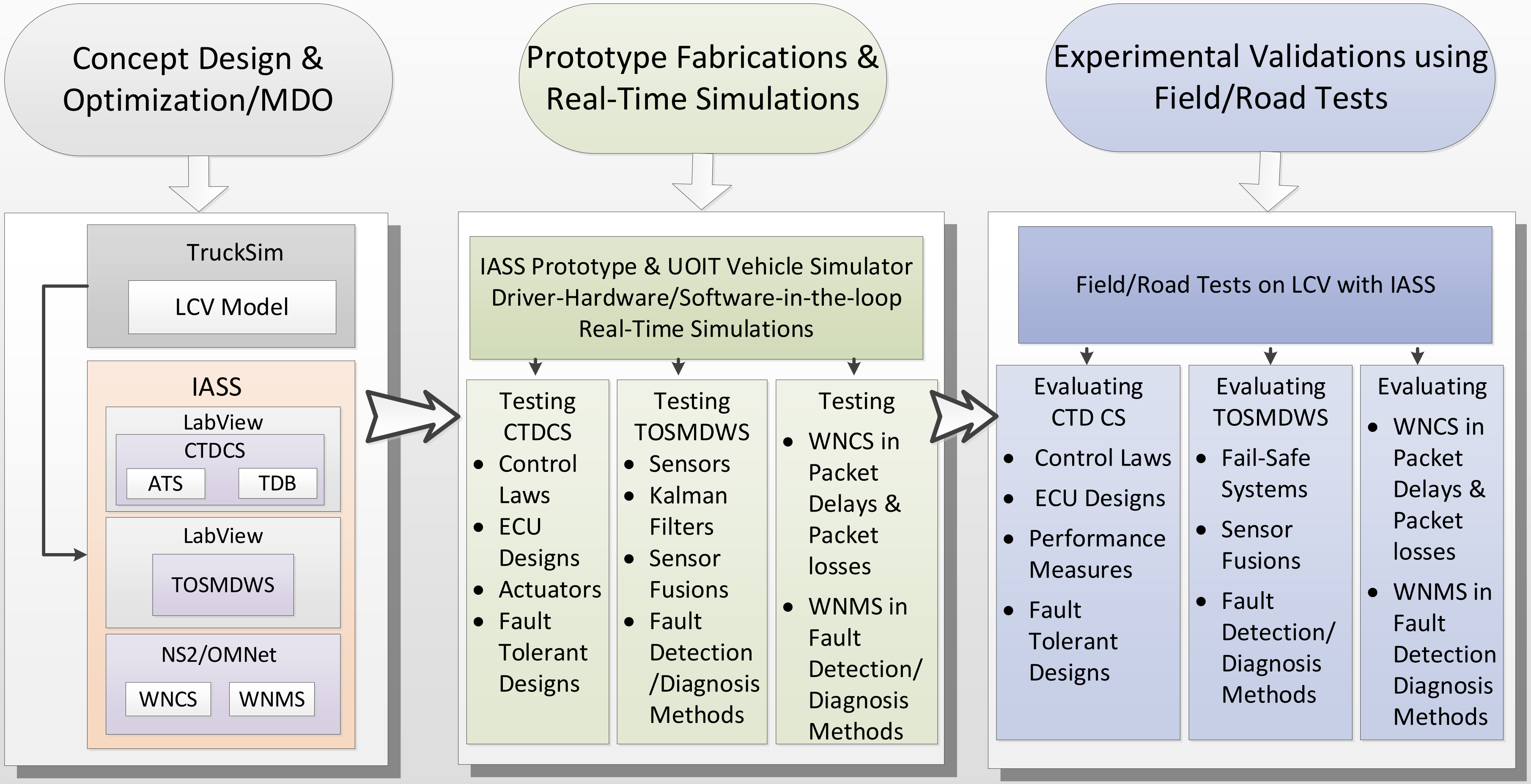
1. ATS operating continuously under high-speed curved or evasive maneuvers with non-aggressive interaction, thereby benefiting to suppress the aggregated trailer motions of LCVs.
2. ARC activating only when specified static rollover threshold level is reached, which improves the roll stability of LCVs by arising the rollover threshold.
3. TDB being activated only in critical situations where the functionality of ATS is exhausted.
4. IASS coordinating the operation of stand-alone ATS, ARC and ARC for enhancing the overall performance of LCVs.



Effective range of typical active trailer safety systems [6].

Proposed Design Methodology

- **Proposed Design Methodology for Advanced Active Safety Systems for LCVs** [7]



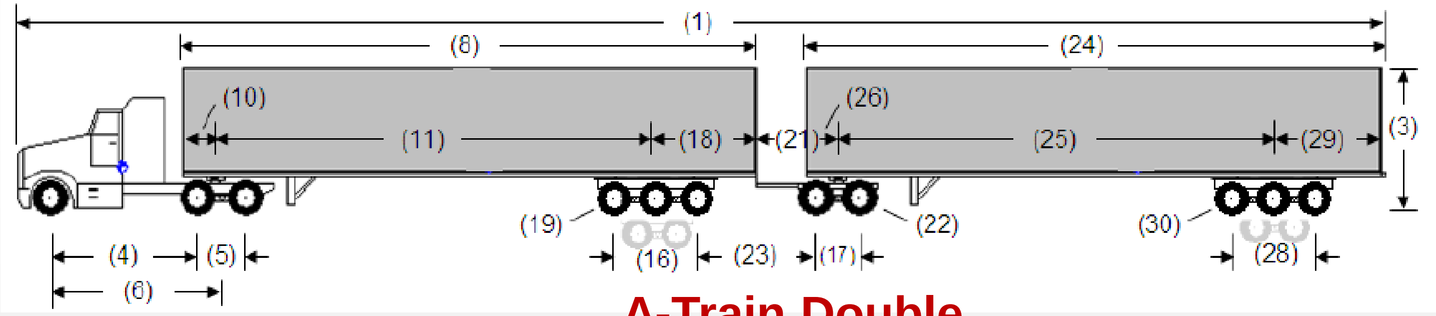
Proposed Design Methodology (cont.)

❑ Features of the Proposed Design Methodology [7]

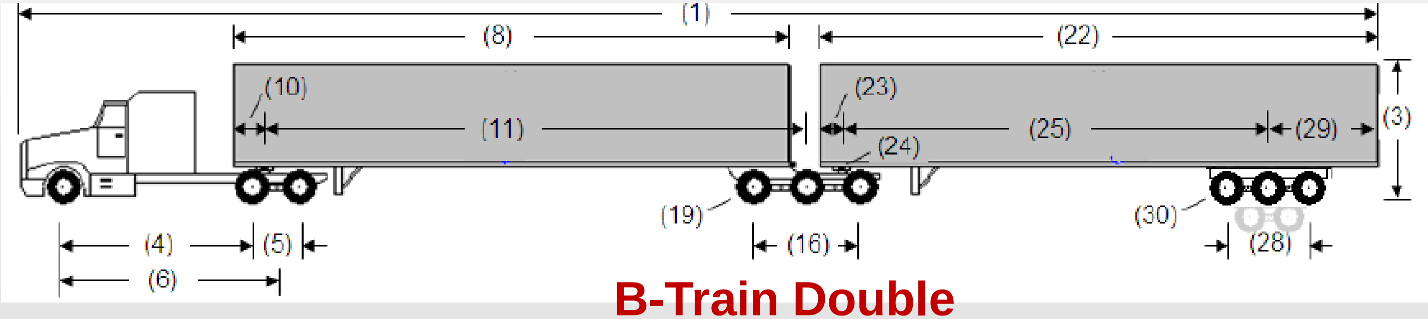
- An IASS design framework provided which considers conceptual design, prototype fabrications, and experimental validations.
- The advanced IASS consisting of:
  1) a coordinated trailer dynamic control system (CTDCS), which is an integration of subsystems of ATA and TDB.
  2) a trailer operating state monitoring and driver warning system (TOSMDWS).
- The CTDCS and TOSMDWS being designed using the wireless networked control system (WNCS) and wireless networked monitoring system (WNMS), respectively.
- The conceptual design being conducted using a proposed model-based design method.
- The prototype fabrications being based on driver-hardware/software-in-the-loop real-time simulations.

Proposed Design Methodology (cont.)

❑ LCVs Studied Using the Proposed Design Methodology [7]

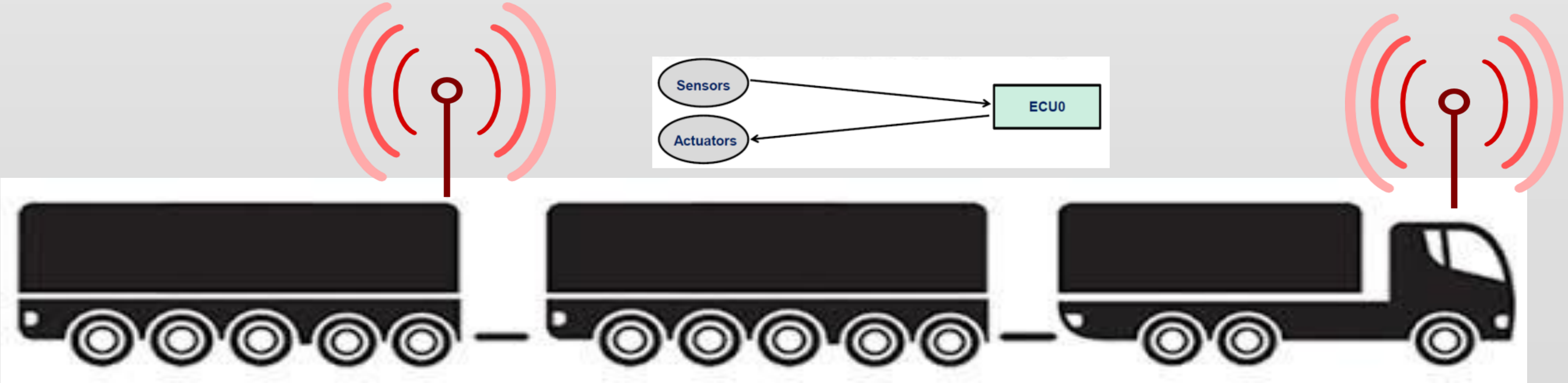


A-Train Double

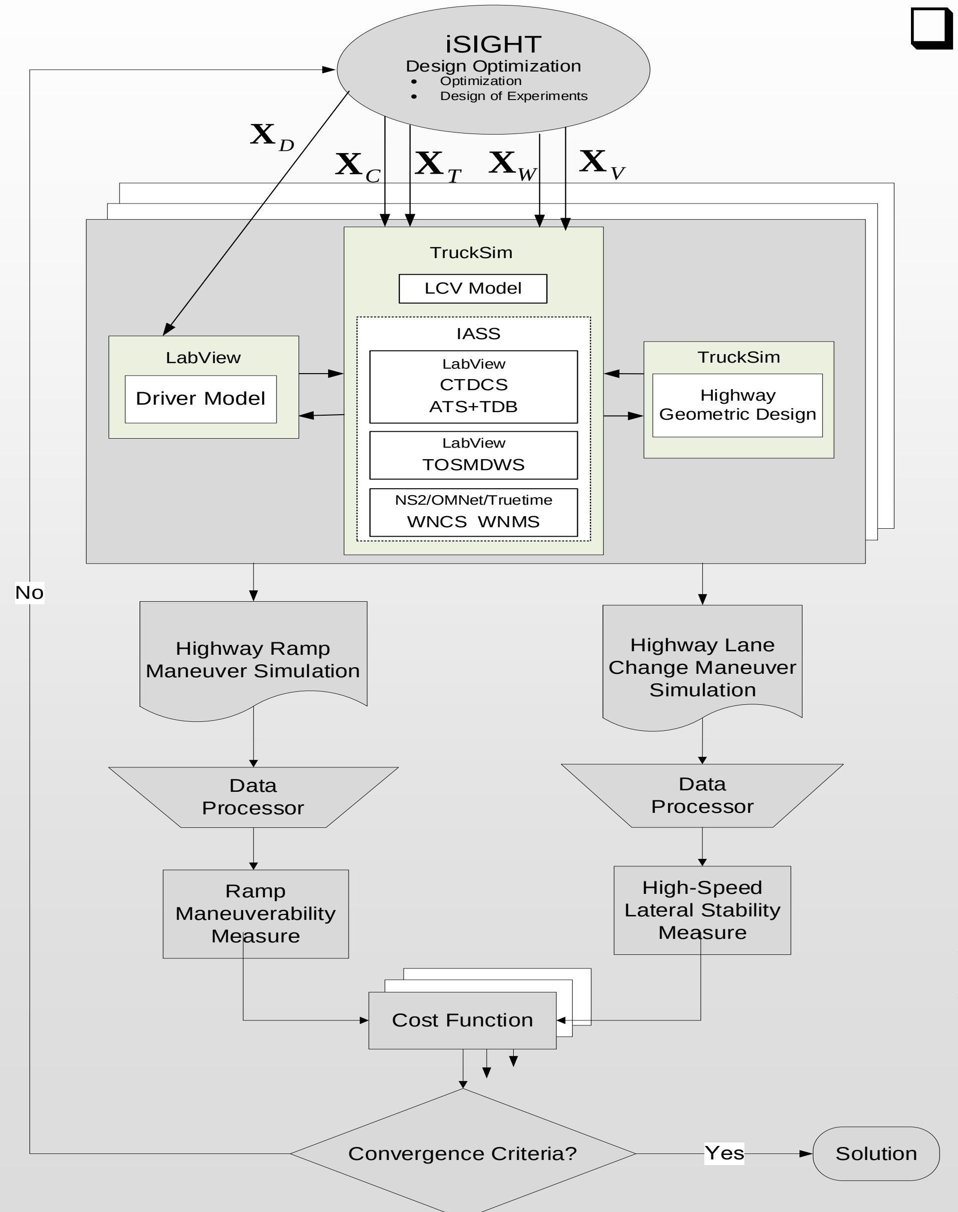


B-Train Double

- The LCVs with the configurations of A- and B-train Double are studied using the methodology.
- Wireless communication technique is used for the wireless networked control system (WNCS) and wireless networked monitoring system (WNMS).



Model-MDO-based Conceptual Design



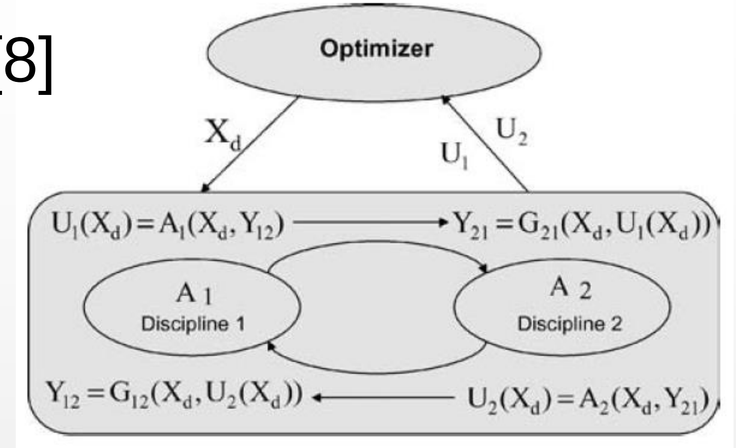
❑ Conceptual Design and Optimization [7]

- Multidisciplinary Design Optimization (MDO) of the IASS, consisting of CTDCS (ATS+TDB) and TOSMDWS based on WNCS and WNMS.
- In the conceptual design, the interactions of Driver-LCV-IASS-Road are fully coordinated and optimized using the MDO method.
- In the MDO, iSIGHT software is used to optimize the coupled systems, and design variables X, including X_D(driver model parameters), X_C(CTDCS variables), X_T(TOSMDWS variables), X_W(WNCS and WNMS variables) and X_V (vehicle variables).
- In the MDO, both low- and high-speed performance measures of the LCV are optimized.

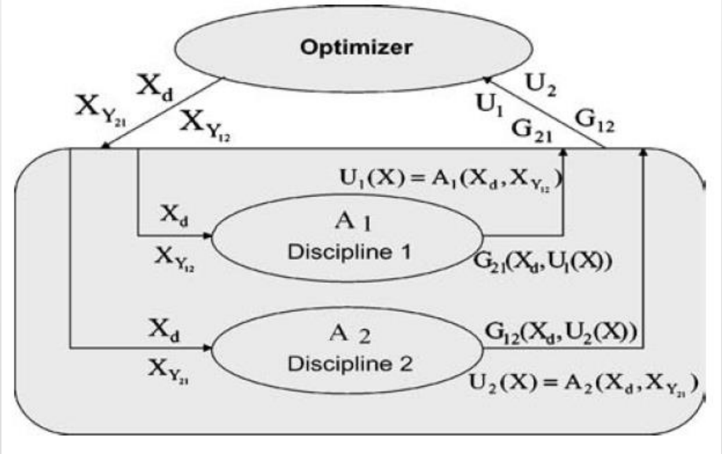
Model-MDO-based Conceptual Design (cont.)

❑ Multidisciplinary Design Optimization Methods [8]

- A successful LCV design requires harmonization of a number of criteria and constraints. Such a design problem can be modeled as a constrained optimization in the design variable space.
- However, for such optimization, due to its dimensionality, complexity, and expense for analysis, a decomposition approach is recommended so as to enable concurrent execution of smaller and more manageable task.
- To preserve the couplings that naturally occur among the subsystems of the whole LCV, such optimization by various types of decomposition must include a degree of coordination at the system and subsystem levels.
- MDO offers effective methods for performing the above optimization so as to resolve the trade-off relations among the various design criteria at the system and subsystem levels.
- In the MDO, the typical methods, e.g., All-in-One and Individual Discipline Feasible methods are applied.



All-in-One (A-i-O) method

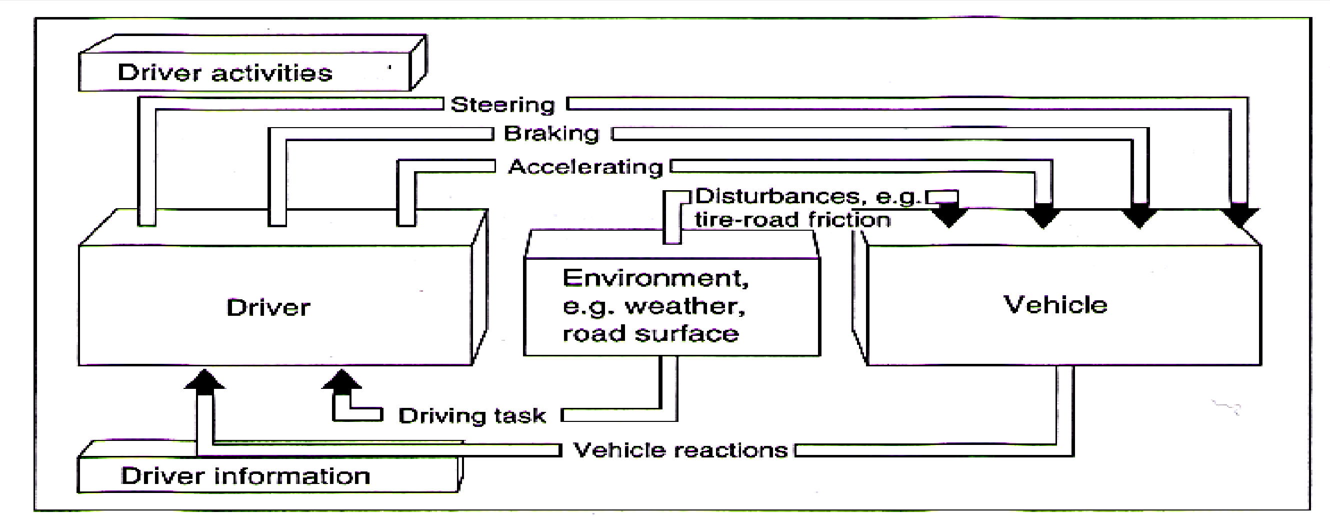


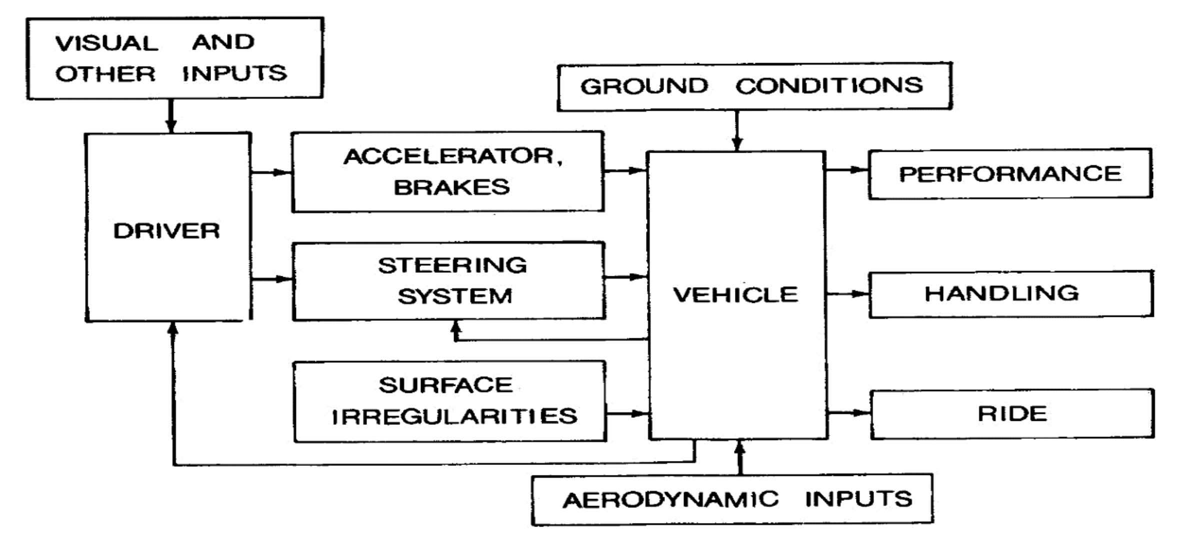
Individual discipline feasible method

Model-MDO-based Conceptual Design (cont.)

❑ Interactions of Driver-LCV-Road [6]

- The directional performance of LCVs has long been studied in open-loop dynamic simulations without considering the driver's dynamic reactions, although the driver may be a destabilizing factor of the vehicle system.
- To consider the driver's impact on the directional performance of LCVs, a closed-loop dynamic simulation-based design method for LCVs with active safety systems has been recommended.
- In the MDO, the model parameters characterizing the driver behaviors are treated as the design variables (virtual driver variables), and the design variables of the LCV and IASS controllers together with the virtual driver variables are optimized simultaneously.

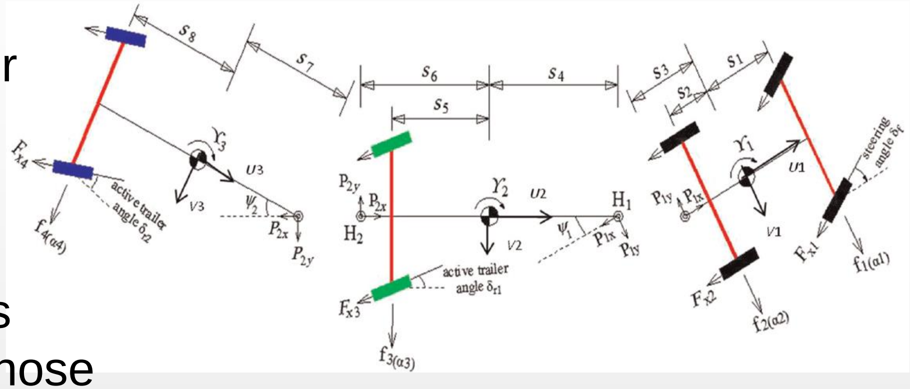




Model-MDO-based Conceptual Design (cont.)

❑ Modelling and Simulation of LCVs [9]

- Different LCV models have various capabilities and limitations for control algorithm development, design optimization and linear stability analysis for LCVs with active safety systems.
- Linear LCV models are effective for estimating the lateral stability and for predicting the dominating motion modes leading to possible instability.
- The performance measures derived from the frequency response analysis using the conventional transfer function approach are in agreement with those achieved using the time-domain simulations of the corresponding non-linear vehicle model.
- The frequency response analysis method may provide an alternative approach to design optimization of a LCV with active safety systems in the frequency domain.
- Under regular evasive maneuvers at low lateral accelerations (lower than 0.35g), linear models are more effective in terms of the fidelity, the complexity and the computational efficiency than non-linear and highly complicated models.
- Linear models should not be used for the design of a lateral-motion controller and optimization of such a system under high-lateral-acceleration (higher than 0.5g) maneuvers.



Linear LCV model

Nonlinear LCV models

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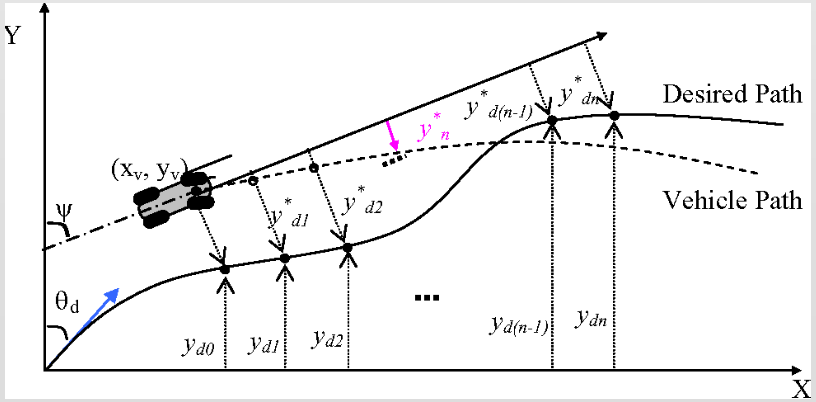
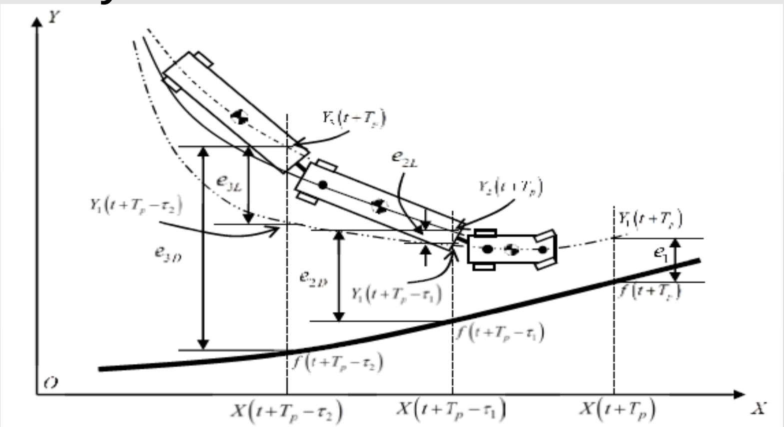
Model-MDO-based Conceptual Design (cont.)

❑ Effective Lateral preview Driver Model of LCVs [10]

- The dynamics of LCVs differs significantly from that of single-unit vehicles. Due to their multi-unit configurations and large sizes, LCVs perform poorly at low speed, and exhibit low lateral stability at high speeds. At high speeds, LCVs often display exaggerated lateral motions of trailing units when executing evasive maneuvers.
- Conventional driver models do not consider the unique dynamic features of LCVs. Thus, these single-unit-vehicles oriented driver models may not effectively simulate LCV drivers' driving behaviors under typical evasive maneuvers.
- An effective lateral preview driver model has been generated for LCVs. This driver model consists of two modes: low-speed mode for path-follow and high-speed mode for lateral stability. In the LCV driver model, the motions cues of trailing units are fully considered.



Driver model for single-unit vehicles

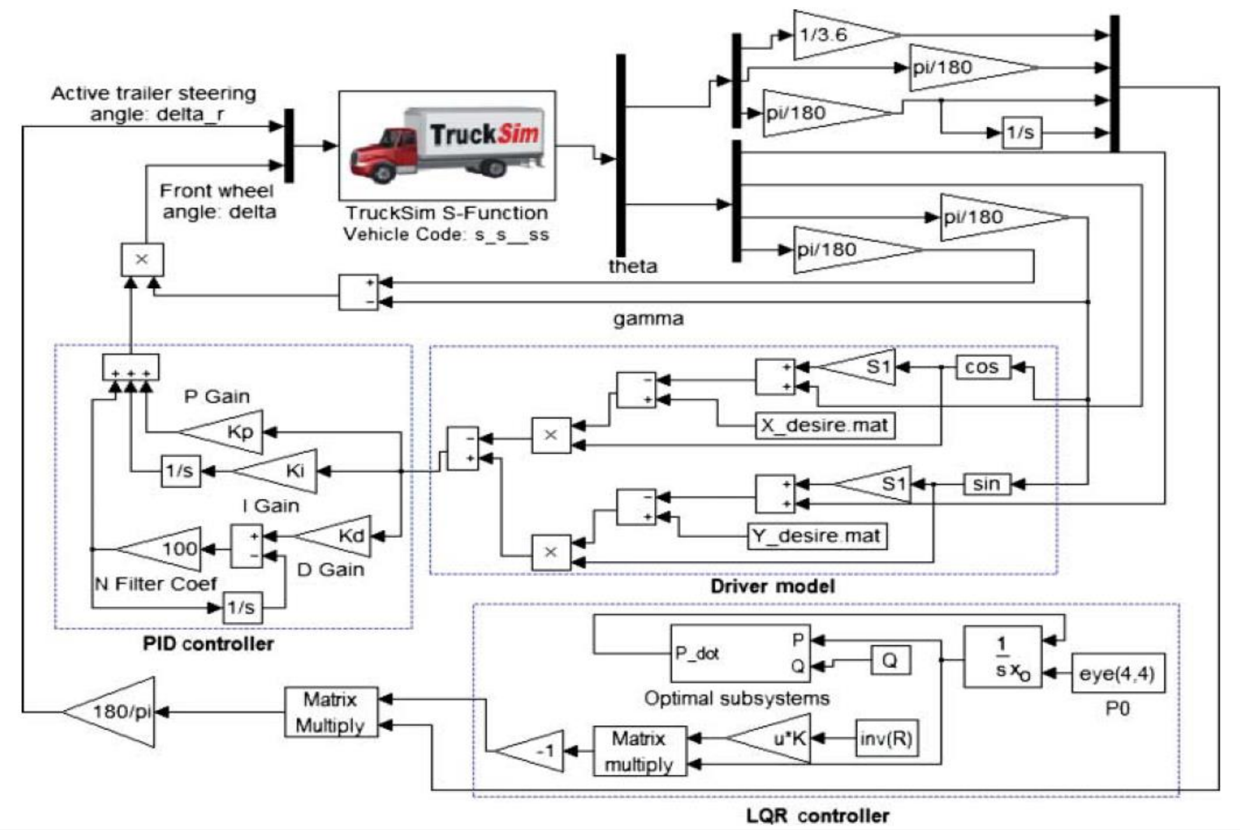


Driver model for LCVs [10]

Model-MDO-based Conceptual Design (cont.)

❑ Closed-loop Co-Simulations for Designing LCVs with Active Safety System [11]

- To fully consider the interactions of Driver-LCV-Controller-Road, closed-loop co-simulations are currently used for the design of active safety systems for LCVs.
- Generally, simplified a linear LCV model is used for controller design for the active safety system. A realistic nonlinear LCV model is generated to represent the LCV. A driver model is developed to simulate the driver’s driving behavior under typical testing maneuvers.
- As shown in the figure on this slide, a controller is designed for an active trailer steering system for an AHV. To this end, a linear yaw-plane vehicle model is generated for the LQR controller for the ATS system, a PID controller-based driver model is developed to represent the driver. A 3D nonlinear vehicle model developed in TruckSim is used for numerical simulation.

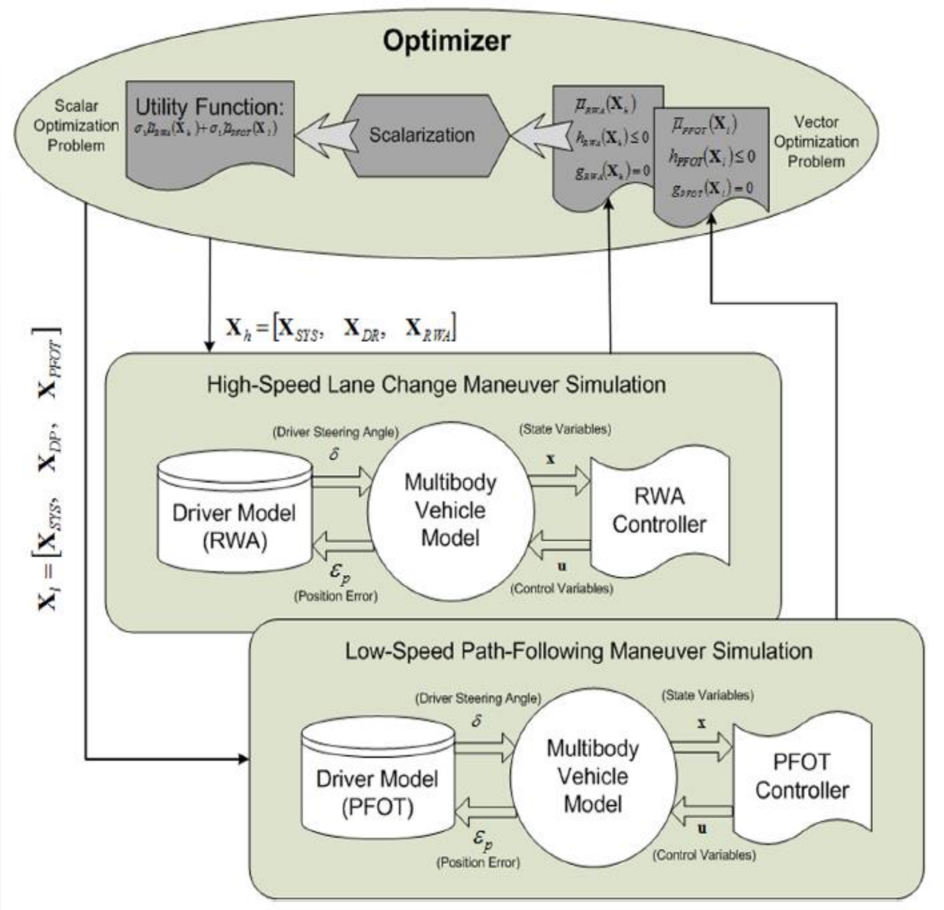


A closed-loop co-simulation environment, integrating AHV model developed in TrunkSim, PID controller-based driver model, and LQR controller for an ATS system [11].

Model-MDO-based Conceptual Design (cont.)

Closed-loop Dynamic Simulation-based Design for LCVs with active safety systems [12]

- To design active safety systems for AHVs with the consideration of interactions of Driver-Vehicle-Controller-Road, a systematic design method has been proposed and developed. This method has the following distinguished features:
  1) A bilevel optimization problem of active safety systems for AHVs is formulated, in which the design criteria related to directional performance measures are formulated at the system level and other criteria are formulated at the subsystem level.
  2) The design variables for the active safety system controllers and the AHV are optimized simultaneously.
  3) Two controllers are designed for the active safety system, for improving stability and enhancing maneuverability, respectively.
  4) A driver model is introduced in the virtual vehicle simulation for closed-loop testing maneuver.
- This design method allows automation of vehicle modelling, controller construction, performance evaluation, and design variable selection, and all required design process are implemented in a single design loop.



A closed-loop simulation-based design method [12].

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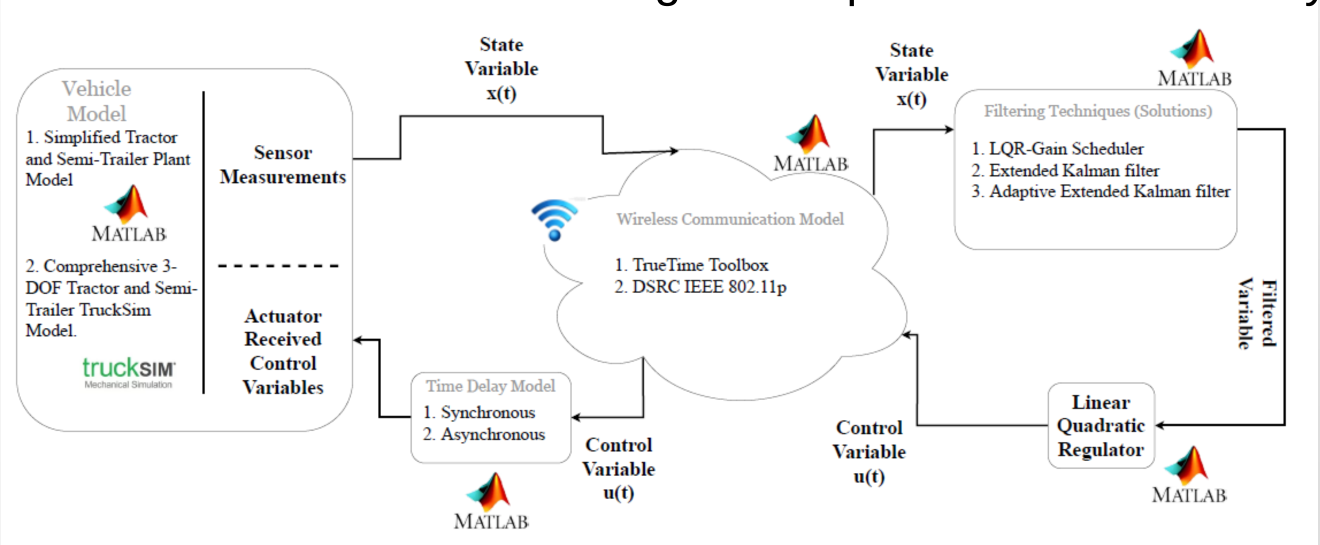
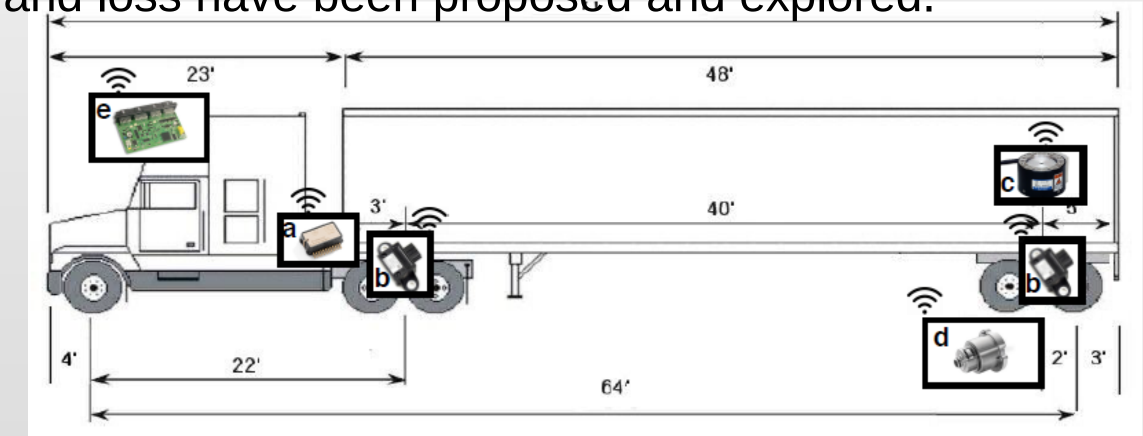
Model-MDO-based Conceptual Design (cont.)

❑ Design of Wireless Networked Control System (WNCS) and Wireless Networked Monitoring System (WNMS) for LCVs [13]

- Conventionally, integrating the sensors, actuators, and controllers located on the leading and trailing units of LCV needs wired connections. The physical connection at the articulation joints increases the risk of disconnections and damages. Adopting a wireless communication system displays pronounced advantages, including flexibility, cost-effectiveness and ease of maintenance.
- Data delay and loss in WNCS and WNMS for LCVs is a design challenge. The effects of important design parameters of the communication system based on dedicated short range communication (DSRC) standard (e.g., modulation, quantization, channel estimation algorithm and transmit diversity) have been studied. Effective solutions to attenuate the negative impacts of the data delay and loss have been proposed and explored.



Co-simulation for the design of WNCS and WNMS for LCVs [13].

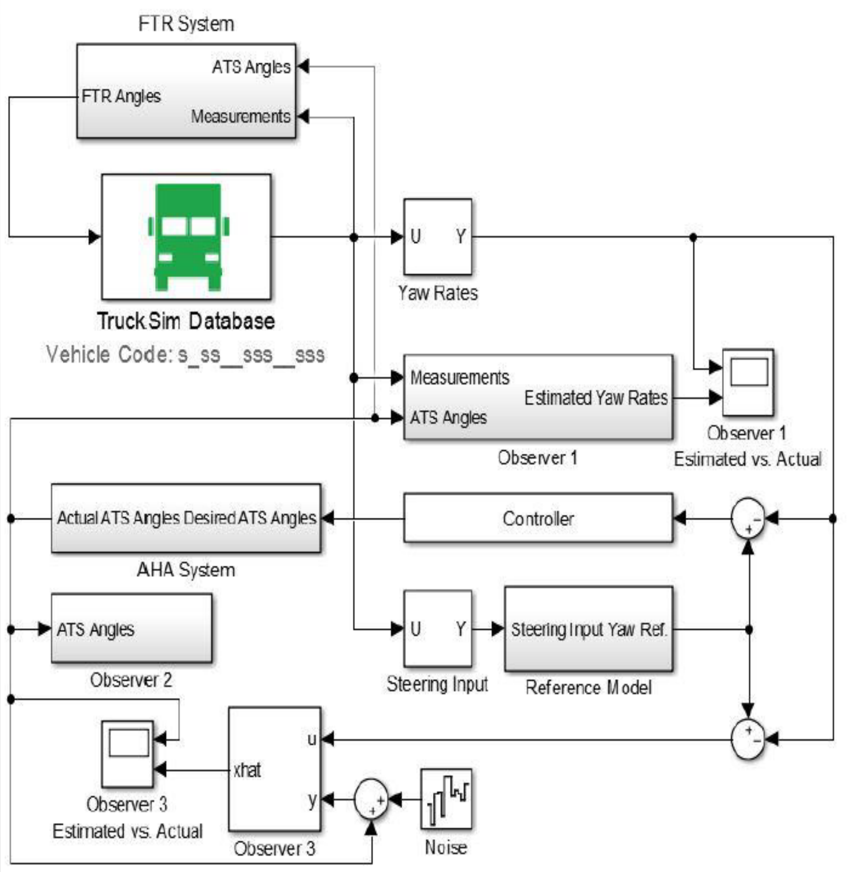


A proposed example for the sensor location on a truck and trailer vehicle combination platform [13].

Model-MDO-based Conceptual Design (cont.)

❑ Fault Tolerant (FT) Design of Active Safety Systems for LCVs [14]

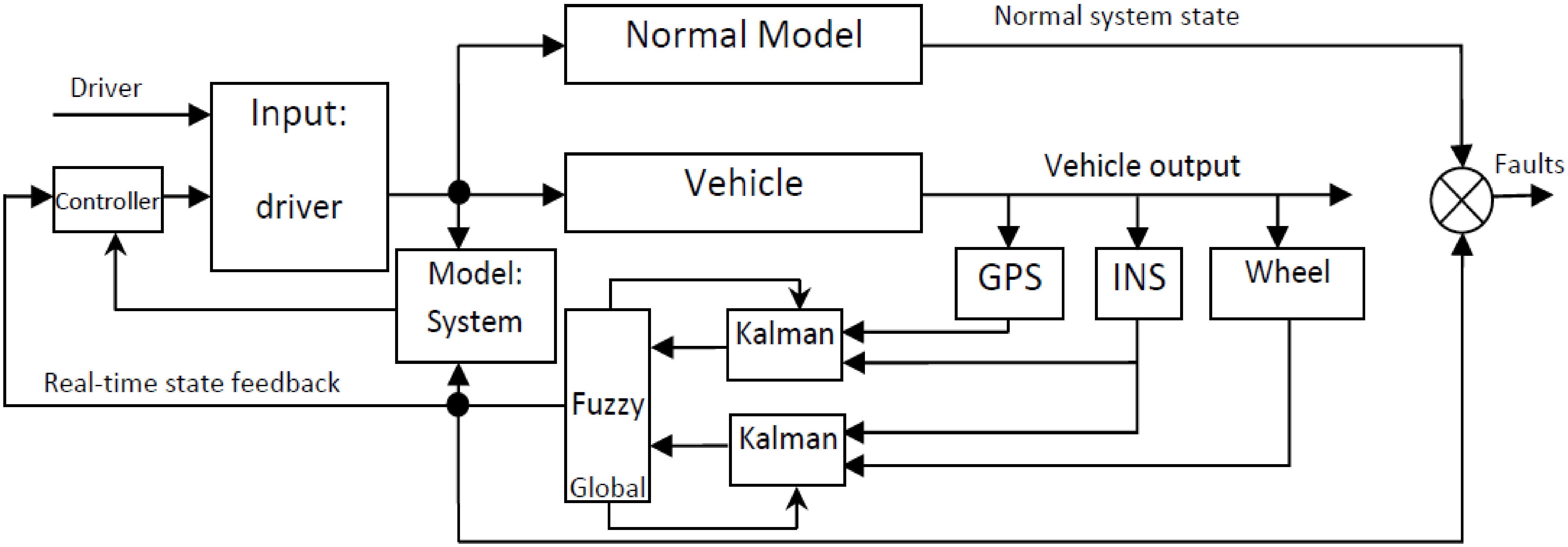
- Faults in an active safety system often deteriorate the LCV performance. In severe cases, faults pose a risk of component damage, safety system shutdown or even personnel safety.
- FT design aims at preventing the escalation of rectifiable faults of active safety system to serious failure.
- An observer-based FT scheme for an active trailer steering system for LCVs is developed.
- The FT scheme comprises of three individual observers, which monitor the designated individual sub-systems. Observer 1 estimates the yaw rate of the vehicle based on the wheel speeds. Observer 2 is responsible for fault diagnosis of the actuation system, whereas Observer 3 monitors the controller and actuation system simultaneously.
- Results indicate that Observer 1 is capable of predicting the yaw rates. Whereas, observers 2 and 3 are equipped to diagnose failures concerning the actuation system and the controller. The combination of these observers generates an effective FT scheme.



A fault tolerant design of active trailer steering system for LCVs [14].

Model-MDO-based Conceptual Design (cont.)

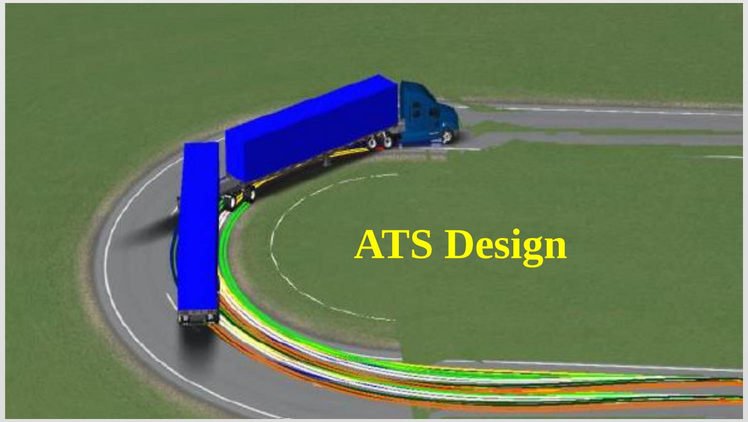
- **Consideration of Sensor Fusion, Sensor and Other Component Fault Tolerance for the IASS** [7]

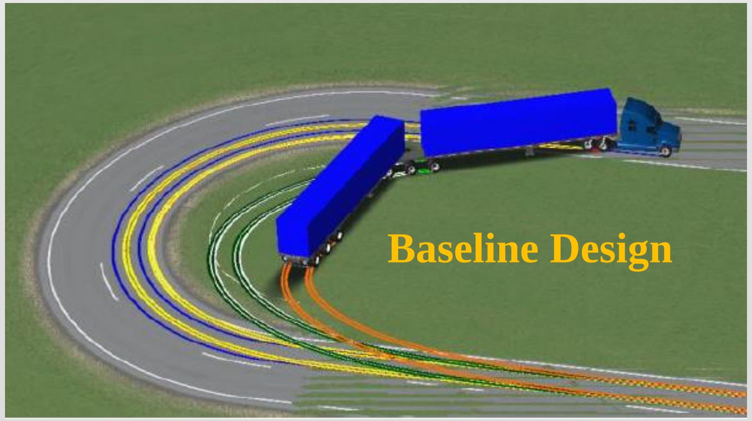


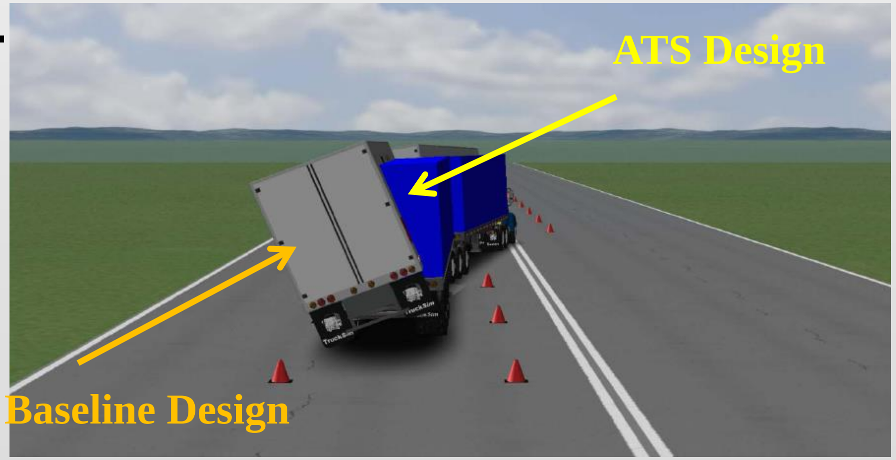
Prototype Fabrications

❑ Virtual Prototypes for LCV Active Safety Systems

- Numerical simulation has been increasingly applied to the design and testing of road vehicles in a virtual environment prior to a physical full-size vehicle prototype being fabricated [15].
- In the Australia performance-based standards for AHVs, both in-vehicle testing and simulation are allowed to evaluate the lateral dynamics of LCVs [16].
- The following figures indicate that a virtual ATS prototype can improve both low-speed path-following performance and high-speed stability [7].



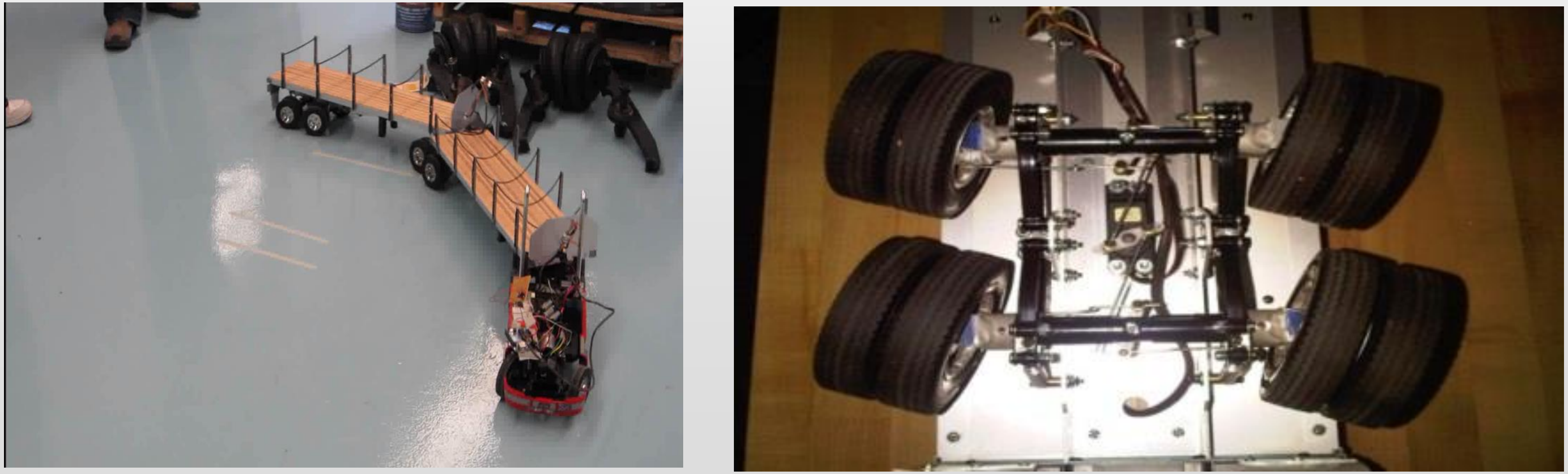




Prototype Fabrications (cont.)

❑ Small-scaled Prototypes for LCV Active Safety Systems

- Small-scaled prototypes are cost-effective for validating the low-speed path-following performance of LCVs with active safety systems [7].
- For validating the high-speed lateral stability of active safety systems for LCVs, the dynamic similarities of small-scaled prototypes should be fully considered and ensured.



A small-scaled LCV with active trailer steering system [7]

Cost-effective Testing and Validating Methods

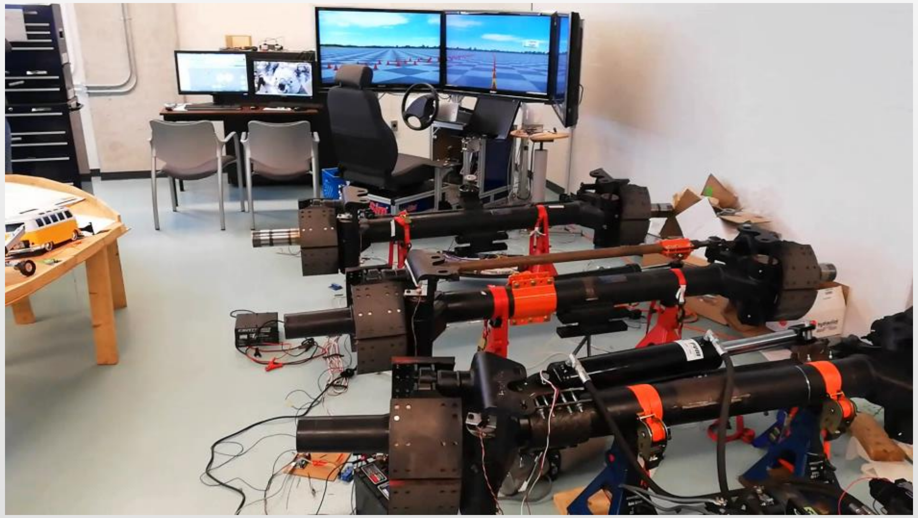
❑ Driver-Hardware/Software-in-the-Loop Real-time Simulations

- To test and validate an active safety system, closed-loop tests may be conducted on fields or roads with the corresponding physical prototypes. However, this process can be difficult, time consuming and costly to accomplish. [17].
- Real-time simulations have been used to assess the impact of new devices, such as ATS systems. The application of real-time simulations to the design of vehicle ASSs can reduce expensive field tests, can facilitate the examination of interactions between the driver, the vehicle and the controller and can resolve critical safety issues prior to in-vehicle testing.
- Driver-Hardware/software-in-the-loop real-time simulations paves the way to development of electronic control units for the active safety system.

Cost-effective Testing and Validating Methods (cont

❑ Driver-Hardware/Software-in-the-Loop (DH/SIL) Real-time Simulation Platform at Ontario Tech University [18]

- The DH/SIL real-time simulation platform provides an effective way to investigate the vehicle–driver–road interactions in a safe and effective way.
- The DSIL real-time simulations are implemented by the integration of TruckSim and LabVIEW Real-Time software.
- The simulator consists of a host computer, an animator computer, a real-time personal computer (PC) and three 46 in monitors, and these units are connected by a controller area network (CAN) and an Ethernet network.
- In a DSIL simulation, the driver drives the virtual MTAHV by manipulating the steering wheel, throttle, brake and clutch pedals. The analogue or digital input signals are fed to the target PC via the data acquisition (DAQ) system and the CAN. The host computer runs the TruckSim and LabVIEW software, transfers the processing signals between the rendering engine and controllers and provides a virtual environment for the animator computer.



Driver-hardware/software-in-the-loop real-time simulation platform [18]

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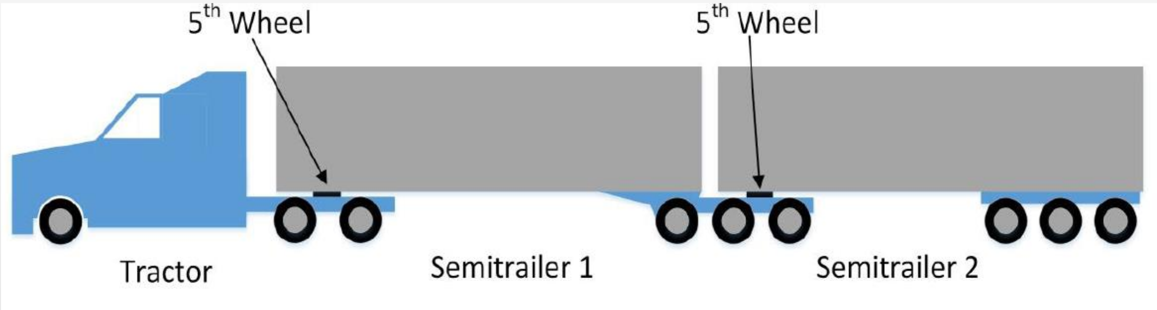
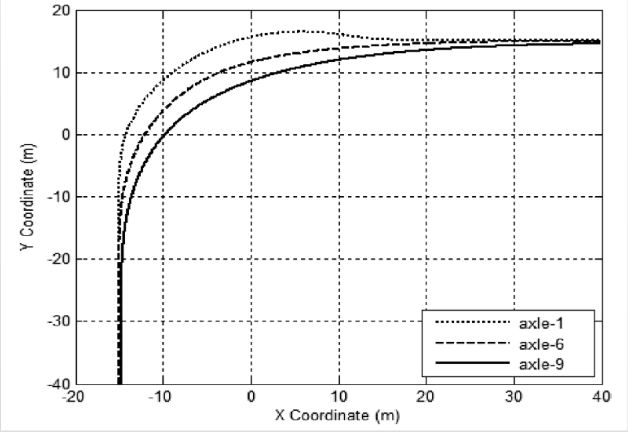
Cost-effective Testing and Validating Methods (cont

❑ Validating Low-Speed Path-Following Performance of an ATS System Using DSIL Real-time Simulations [18]

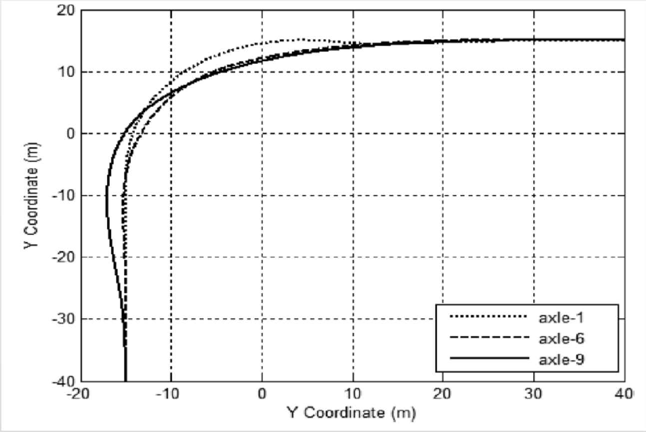
- A design validation for an ATS for improving low-speed maneuverability of a B-train double using DH/SIL simulations.
- The ATS can improve the low-speed path-following performance and reduce the trailer tire wear while negotiating a tight corner.



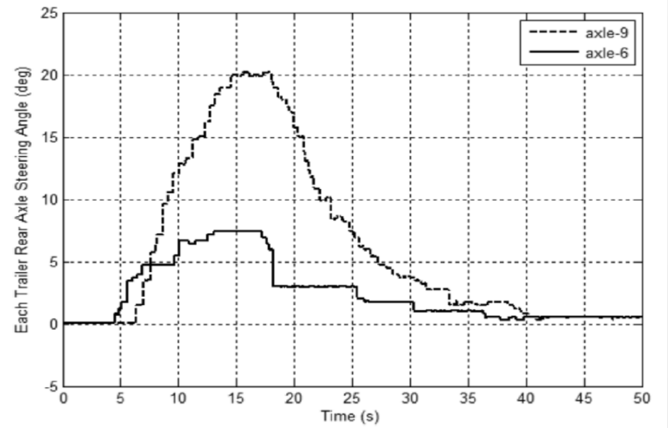
- In curved path negotiations, the ATS system can mitigate the driver's steering effort.



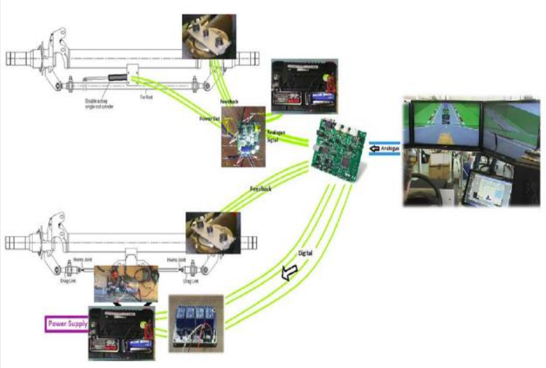
Trajectories of axle centres of LCV in the 90° turn (baseline case)



Trajectories of the axle centres of LCV in 90° turn (ATS case)



Time history of the steering angle of the wheels on axle-6 and axle-9 for the ATS case



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Conclusions and Future Research

- Government Standards and Regulations have no specified requirements on active trailer safety systems, e.g., ATS, TDB, ARC, etc., for trailers of LCVs. However, only ESC system on the tractor is not sufficient to control the amplified lateral motions of trailing vehicle units.
- Individual active trailer safety systems have their applicability and effective operating ranges. To ensure good overall directional performance of LCVs, coordinating individual active trailer safety systems is recommended.
- A model and multidisciplinary design optimization (MDO) based design methodology has been proposed and explored for the active safety design for LCVs. In the active trailer safety system design, the methodology considers the interactions of Driver-LCV-Controller-Road.
- Numerical and real-time simulations demonstrate the effectiveness of the proposed Model-MDO based design methodology. The effectiveness of the design methodology should be further validated using road/field in-vehicle tests.

Conclusions and Future Research (cont.)

- Fault Tolerant Design for Active Safety Systems of LCVs Needs to Be Further Explored In The Future.
- Real-Time Simulations and Prototypes of Wireless Networked Control System (WNCS) and Wireless Networked Monitoring System (WNMS) for LCVs Need To Be Conducted and Fabricated to Demonstrate the Effectiveness of WNCS and WNMS For Active Safety Systems of LCVs.
- Integrating Autonomous Driving and Active Safety Technologies Will Be Future Research Efforts.

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