Rollover Warning/Control for Sports Utility Vehicles

Bo-Chiuan Chen, GSRA
Huei Peng, Associate Prof.

Dept. of Mechanical Engineering and Applied Mechanics
University of Michigan
Outline

• **Introduction**

• TTR Warning/Anti-Rollover Control

• TTR Robustness Study

• Human-in-the-Loop Evaluation of the TTR Based Anti-Rollover Control

• Conclusion
Rollover Fatality Rates

Source: 1991-94 Average/Annual deaths per million registered vehicles provided by United States Department of Transportation
Why SUVs Roll Over

SUV
High center of gravity: Sideways force can cause rollover.

SEDAN
Low center of gravity: Resists rollover.

Similar width between wheels
• Introduction

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Time To Rollover (TTR)

- **TTR**: Index defined to assess rollover threat in this research.

![Diagram of Time To Rollover (TTR)]
Desired TTR

• For rollover cases, a straight line with \(\text{slope} = -1\) is created starting from the rollover point backwards in time.

• It gives a uniform “countdown” toward rollover threats and thus serves well as the basis of warning/control.

\[TTR=0.5\]  The vehicle will rollover 0.5 sec later.
Neural Network (NN) Architecture

Train NN to approach the Desired TTR

Layer 1

Layer 2

inputs

Roll Angle

Change of Roll Angle

TTR from Simplified Model

Desired TTR

output

NN TTR

- +

Intelligent Vehicle Dynamics and Control
TTR Based Anti-Rollover Control

Controller

Reference TTR

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Differential Braking

\(*\)

Braking Moment

Lateral Acceleration

Steering Input (Disturbance)

TruckSim Cherokee

TTR Calculation

TTR

Intelligent Vehicle Dynamics and Control
Previous Studies

**ARC 1998**

Rollover Warning of An Articulated Heavy Truck

**ARC 1999**

Rollover Warning and Control of Sport Utility Vehicles

Introducing the International® 9000i Series
Ramp steering

Entering ramp

Obstacle avoidance

Worst-case

Without Worse Case Training
Fz of the left front tire

Fz of the right front tire

Fz of the left rear tire

Fz of the right rear tire

No control

P-control
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TTR Robustness Study

- Ramp radius & Superelevation angle: $(\infty, 0^\circ)$ vs. $(100\text{m}, 10^\circ)$
- Vehicle load & C.G. Height: Empty vs. Gross (45% more of the empty weight)
- Tire pressure: 33 psi vs. 16.5 psi
- Road friction: 0.85 vs. 0.3
- Speed: 30 mph vs. 60 mph
- Sensor noise:
  - Steering, longitudinal speed, lateral accel., roll angle
  - Noisy vs. Clean measurement
Superelevation

Speed = 50 mph
Radius = 100 m
Sup. = 10°

Lack of the superelevation info.
Gross Load Condition

Misdetection
(False negative reading)
Tire Pressure vs. Tire Stiffness

Longitudinal Force

![Graph showing longitudinal force vs. slip ratio and tire pressure vs. stiffness.]

Lateral Force

![Graph showing lateral force vs. slip angle and tire pressure vs. stiffness.]

Aligning Moment

![Graph showing aligning moment vs. slip angle and tire pressure vs. vertical stiffness.]

Vertical Stiffness

![Graph showing vertical stiffness vs. tire pressure.]

33 psi

16.5 psi
Tire Pressure Effect

Nominal pressure: 33 psi
Low pressure: 16.5 psi
Road Friction

\[ \mu = 0.85 \]

\[ \mu = 0.3 \]

TruckSim TTR

Simple TTR

False Alarm
(False positive reading)
Gain-scheduling works well for the test cases (step steering).
Sensor Noise

No Sensor Noise

With Sensor Noise

TruckSim TTR

Simple TTR

TTR (sec)

time (sec)
Robustness Solution

• Low tire pressure and speed are not significant for the test cases (step steering).

• Sensor noise can be handled by low-pass filters.

• Superelevation, road friction, and gross load condition can be handled by the adaptive TTR algorithm.
Low-Pass Filter

Without Filter

With Filter

T delay

Simple TTR

TruckSim TTR

Depends on the signal offset and the filter cut-off frequency.

Intelligent Vehicle Dynamics and Control
Adaptive TTR Algorithm

- Gain-scheduling for gross load condition

Steering angle

Yaw Model 1

Lateral acceleration

Roll Model

Roll angle Roll rate

Braking torque

Yaw Model 2

Coupling Gain 1

Coupling Gain 2

Coupling Function

\( \hat{a}_y \) (for initial conditions)

\( a_{y\_sensor} \)

\( \hat{a}_{y\_superelvaton} \)

\( \mu \)
Friction Adaptation

$\mu = 0.3$

$\mu = 0.5$

Simple TTR

TruckSim TTR
Superelevation

![Graphs showing steering, roll, lateral acceleration, and TTR over time.](image)

- Steering (deg)
- Roll (deg)
- Lateral accel. (g)
- TTR (sec)

Intelligent Vehicle Dynamics and Control
Gross Load Condition

Without Gain-Scheduling

With Gain-Scheduling

TruckSim TTR

Simple TTR
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Driving Simulator Setup

- SGI Onyx2 Graphics Supercomputer
- VVSS Graphics
- Dell Inspiron 5000 PIII 600Mhz Notebook
- TruckSim Dynamics
- Microsoft Force Feedback Steering Wheel
Calspan - MOTS Driving Course

Diagram of the Calspan - MOTS Driving Course with labeled sections:

1. Lake driving
2. Wet surface
3. Exit chute & braking
4. Off-shoulder recovery

Legend:
- Start
- Finish
- "S" section
- Avoidance maneuvers
① Large Radius Arc

Inner Radius = 200 ft
Outer Radius = 212 ft
Lane width = 12 ft
Avoidance Maneuver

Obstacles

Unit: ft
3 Small Radius Arc

Inner Radius = 140 ft
Outer Radius = 152 ft
Lane width = 12 ft
4) Fishhook Maneuver

1\textsuperscript{st} Radius = 75 ft
2\textsuperscript{nd} Radius = 150 ft
Lane width = 12 ft
Human-in-the-Loop Evaluation

• Each test subject is required to drive 3 vehicles.
  - No control.
  - Control with differential braking.
  - Control with just braking on the front axle.

• Each vehicle is driven through 4 MOTS scenarios.

• 18 people participated the evaluation. The types of vehicles are not revealed until the end of the experiment.

• Because of the drivability concern, the braking torque is limited at 250 N-m for differential braking and 125 N-m for both front wheels of the front braking.
Drivers use *lateral velocity* and *yaw rate* for the steering decision.
Evaluation Results

Differential Braking  Front-axle Braking

Larger $F_{z\_min}$

Smaller $Roll_{\_max}$

Smaller $Ay_{\_max}$

* success rate (%) = \frac{\text{# of success}}{18 \text{ tests}}
Verification Results

Differential Braking

Front-axle Braking

Larger $F_{z_{\text{min}}}$

Smaller $\text{Roll}_{\text{max}}$

Smaller $\text{Ay}_{\text{max}}$

Large Radius Arc

Avoidance Maneuver

Small Radius Arc

Fishhook Maneuver

* success rate (%) = \[
\frac{\text{# of success}}{18 \text{ tests}}
\]
Human-in-the-loop

- The controller was designed and verified under the given step steering and fishhook steering. *BUT not with human-in-the-loop.*

- Human close the loop of the *vehicle* and the *environment*. Drivers might feel the vehicle equipped with the anti-rollover control difficult to drive and thus degrade its performance.

- *Driving Simulator* can be used to verify the control performance and collecting driving patterns for controller design.
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Conclusion

• An Adaptive TTR algorithm was proposed to enhance the TTR robustness against the variation of the superelevation, road friction, and the gross load condition.

• Anti-rollover control did not perform well with human-in-the-loop evaluation. We will design a more complicated or better tuned controller.

• Active safety device should be designed and evaluated with human-in-the-loop to guarantee the performance.