Development and Evaluation of a Novel Traffic Friendly Commuter Vehicle

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Highway Congestion

- Traffic congestion is a significant - and growing - problem in the country’s major metropolitan areas

- Some statistics
  - Average traffic delay due to congestion grew 235% between 1982-1997
  - Uncongested travel fell from two-thirds of travel in 1982 to one-third travel in 1997
  - The increase in traffic demand every year exceeds the increase in capacity due to new construction
    - Traffic congestion will continue to become worse
Approaches to Addressing Highway Congestion

- What solutions do researchers in the automotive industry and researchers in the vehicle dynamics community offer to highway congestion?
  - Automated highway systems
  - Intelligent adaptive cruise control systems
Automated Highway Systems

- AHS lanes will have three times the capacity of regular highway lanes - Vehicles will travel together in closely-packed “platoons”.
- Dedicated to automated vehicles - regular passenger cars will have to be specially instrumented to travel on AHS lanes.

- AHS is “dual mode” transit
  - Your instrumented car can travel on AHS and can also take you on regular roads
Automated Highway Systems

- NAHSC demonstration in 1997
- Demonstration operated continuously several hours a day for 3 weeks
  - Passenger rides given to over 1000 visitors

Video
Automated Highway Systems

● A variety of challenges need to be addressed before AHS can become a reality
  – technical
  – economic
  – social
  – legal

● The AHS concept received a setback with the demise of the NAHSC
Adaptive Cruise Control

Without preceding vehicle

Maintain constant speed

With preceding vehicle

Maintain safe distance

radar
Adaptive Cruise Control

- **Typical ACC System**
  - Constant time-gap (CTG) spacing between vehicles

\[ \text{Desired spacing} = L + hv \]

- **Research Questions**
  - Should ACC systems be designed to maintain a constant time-gap between vehicles?
  - Can traffic capacity and safety be simultaneously improved by clever ACC design?
Narrow Commuter Vehicles

- **Motivation**
  - Double highway capacity by using a half-width lane instead of a regular highway lane
  - **Motorcycles**
    - take up less space on the highway
    - need less space for parking
    - are fun to drive
    - are *energy efficient*

- **Can we develop a narrow vehicle that can**
  - provide the benefits of a motorcycle
  - the safety of a car
  - be as easy to drive as a car?
Narrow Commuter Vehicles

A narrow vehicle needs to tilt into a curve for stability
Project Objective

- Develop an automatic control system that
  - Keeps the vehicle balanced while it is traveling straight
  - Tilts the vehicle into a curve during cornering
  - Reduces acceleration experienced by the driver
  - Always maintains vehicle stability
Some interesting prototype narrow vehicles

- The Volkswagen 1-liter car

Volkswagen’s objective: Develop a prototype vehicle that can provide 100 km/liter (250 miles / gallon !)
  - Solution: A narrow vehicle two-seater platform, aerodynamic design, lightweight carbon-fiber reinforces composite body
  - Very agile handling, provides driving pleasure combined with a fuel economy never seen before
Some other interesting prototype narrow vehicles

Fig. 1 Ford “Gyron” (1961)

Fig. 2 GM “Lean Machine” (1983)

Fig. 3 Daimler “Life Jet” (1997)

Fig. 4 “Carver” (2003)
Control system - Dynamic Model

Fig. 5 Degrees of freedom

\[ m\ddot{y} + m\dot{\psi}V + \ddot{\theta}hm (\theta) - m\dot{\theta}^2 h \sin(\theta) = F_f + F_r + mg \sin(\beta) \]
\[ I_z \ddot{\psi} = l_f F_f - l_r F_r \]
\[ I_x \ddot{\theta} = (-\ddot{\theta}hm \sin(\theta) - \dot{\theta}hm \cos(\theta) + mg \cos(\beta))h \sin(\theta) - (F_f + F_r)h \cos(\theta) + T \]

(1)

Fig. 6 Bicycle model
Driver Model: *Look-ahead-error based model* (Guldner et al. 1996)

\[
\text{Driver Input} = -k \left( e_1 + e_2 ds \right) + \delta_{ff}
\]

*Parameters can be defined as a function of velocity to account for driver steering behavior change due to velocity variations.*
Tilt Control Systems

Possible actuation systems

- **Direct tilt control (DTC)**
  - An independent actuator is used to provide tilt torque
  - Tilt and lateral dynamics can be independently controlled
  - For low speed operation (less than 5 m/s or 11.18 mph).

- **Steering tilt control (STC)**
  - Steering angle is used to control both tilt and lateral position
  - Challenge: One control input, two control tasks
  - For high speed operation (higher than 10 m/s or 22.37 mph).
Introduction – Proposed control system

Fig. 8 Control scheme
Direct Tilt Control (DTC)

a) Simple approach (stand alone):

\[ \theta_{des} = \frac{\ddot{y}V}{g} = \frac{V^2}{Rg} \]

b) Proposed approach I (stand alone):

\[ \theta_{des} = \frac{(\ddot{y} + \dot{y}V) - 2(I_{wheel_{\psi}} - I_{wheel_{rot}})\omega_{rotation}\dot{\psi} / (hm)}{g} \]

- Accounts for lateral acceleration of vehicle in addition to centripetal acceleration.
- Accounts for gyroscopic moment due to rotating wheels.
- Results in a significant reduction in transient tilt torque requirement.
- Results in zero tilt torque requirement at steady state.

c) Proposed approach II (Integrated):

\[ \theta_{des} = ks(Driver_{input}) = ks(-k(e_1 + d_se_2) + \delta_{ff}) \]
Steering Tilt Control (STC)

- **Steer-by-wire system**
  - Driver steering input is modified before being used to steer the wheels
  - Driver input is interpreted as a desired tilt angle
    - With appropriate definitions, leads to the same steady state value of steering angle

\[
\theta_{des} = ks(Driver\_input) = ks(-k(e_1 + d_1 e_2) + \delta_{ff})
\]

\[
\delta = k_3(\theta - \theta_{des}) + k_4(\dot{\theta} - \dot{\theta}_{des}) + k_5 \theta_{des} e^{-\nu(\theta - \theta_{des})}
\]
Control system - *Combined system (SDTC)*

- Both STC and DTC used in parallel.
  - DTC active at low vehicle speed.
  - STC active at high vehicle speed.

\[
\alpha = \begin{cases} 
1 & \text{if } V < V_o \\
\frac{1}{2} \left[ 1 + \sin \left( \frac{\pi (V - V_o)}{(V_o - V_f)} \right) + \frac{\pi}{2} \right] & \text{if } V_o < V < V_f \\
0 & \text{if } V > V_f 
\end{cases}
\]

(9)

\[
\beta = 1 - \alpha
\]

\[
\delta = \beta \left[ k_3 (\theta - \theta_{des}) + k_4 (\dot{\theta} - \dot{\theta}_{des}) \right] + k_i \int (\theta - \theta_{des}) dt
\]

(10)

\[
T = \alpha \left[ -k_1 (\theta - \theta_{des}) - k_2 \dot{\theta} \right]
\]
Control system - Tilt Brake

Start

Brake on
\[ \theta = 0 \]
\[ \delta = \text{driver input} \]

\[ V \]

\[ V > V_{\text{min}} ? \]

Yes

Brake off
\[ \theta_{\text{des}} = k_s \times \text{driver input} \]
\[ \delta = k_r (\theta - \theta_{\text{des}}) + k_e (\theta_{\text{des}} - \theta) + \delta_0 \]

\[ V \]

\[ V < V_{\text{min}} ? \]

Yes

No

No

Yes

\[ V > V_{\text{min}} \]

\[ |\text{driver input}| < \varepsilon_1 ? \]

\[ \delta + - + - = (\theta - \theta_{\text{des}}) \]

\[ \theta_{\text{des}} = 0 \]

|\theta| < \varepsilon_2 ?

Yes

No

Brake on
\[ \delta = \text{driver input} \]

\[ \theta \]

Fig. 14 Tilt brake algorithm
Prototype

Fig. 15 Second generation prototype
Prototype - Design

Vehicle Specifications

- Engine: 125cc Yamaha
- Longitudinal acceleration: ± 0.7 g
- Tilt limit: ±30°
- Bump limit: ±15° (0.1 m)
- Steering limit ±30°
- Rake angle: 9.5°
- Front wheel trail: 0.06 m
Prototype - Tilt mechanism

Video

Fig. 17 Vehicle tilt mechanism
Prototype - Tilt Mechanism actuation

Fig. 18 Tilt motor
Prototype - Steering Mechanism

(a) Direct steering

(b) Steer-by-wire

Fig. 19 Steering system
Prototype - Tilt Brake System

Fig. 20 Tilt brake
Prototype - Instrumentation

Reference input
- Driver input

Sensors
- Absolute encoder
- Incremental encoder 1
- Incremental encoder 2
- Hall effect sensor
- Xbow IMU

States
- Tilt angle
- Steering angle
- Speed
- ay, ax, az
- yaw, pitch, roll

Ref. input

Control inputs
- PC - 104 IBM computer

Actuators
- Tilt servomotor
- Steering servomotor
- Tilt brake electromagnet

Fig. 21
**Simulation – DTC (Simple Vs. Proposed)**

Operating conditions:
- Vehicle velocity: 5 m/s (11 mph).
- A desired trajectory of a straight line for the first 50 seconds followed by a circular path of radius 8 m (26 ft).

![Fig. 22 Tilt torque requirement](image-url)
Simulation – \textit{DTC (Simple Vs. Proposed)}

\begin{itemize}
  \item \textbf{a. Proposed approach}
  \item \textbf{b. Simple approach}
\end{itemize}

\textbf{Fig. 9 States}
The SDTC system was simulated for:

- Vehicle velocity varying between 1 m/s (2.24 mph) and 25 m/s (55.92 mph).
- A desired trajectory of a straight line for the first 50 seconds followed by a circular path of radius 500 m (1640.42 ft).

Fig. 29 Velocity profile of vehicle
SDTC Simulation

- Trajectory tracking

![Circular path](image)

![Straight path](image)
Simulation – SDTC

Fig. 32 SDTC - Tilt torque (T)

Fig. 33 SDTC - Steering input (δ)
Simulation – SDTC

Fig. 30 SDTC – Lateral states

Fig. 31 Allowable position error
Experiments

Validate the tilt stability and trajectory tracking.
  • Turn maneuver experiments
  • Lane change maneuver experiments

Validate the tilt brake system.
  • Sinusoid steering input experiments

Vehicle handling investigation.
  • Under steering experiment
  • Neutral steering experiments
  • Constant yaw rate experiments

System limits.
  • Steering subsystem vibration
Experiments - General stability

Video

Fig. 34 Tilt stability
Experiments – Trajectory tracking

Video

Fig. 35 Slalom course
Experiments – Turing maneuver

Fig. 36 Desired tilt angle tracking
Experiments – Turning maneuver

Fig. 37 Vehicle yaw rate
Experiments – \textit{Lane change maneuver}

Fig. 38 Desired tilt angle tracking
Experiments – *Lane change maneuver*

Fig. 39 Vehicle yaw rate
Experiments – *Tilt brake validation*

![Graph showing tilt angle tracking and tilt brake status](image)

**Fig. 40** Tilt angle tracking and tilt brake status
Experiments – Tilt brake validation

Fig. 41 Vehicle yaw rate
Experiments – Neutral steering

Fig. 42 Neutral steering
Experiments – System limitations

Video

Fig. 43 Steering subsystem instability
Experiments – System limitations

Fig. 44 Steering subsystem instability
Conclusion

- A control system that stabilizes an NTV from start up to highway speed while accurately following a desired trajectory was successfully designed.
  - A DTC system that is suited for an integrated SDTC (STC + DTC) system was proposed.
  - A method for smoothly shifting control efforts between the STC and DTC system was developed.
  - A Tilt brake system and algorithm was developed for low speed operation.

- A new stand alone DTC system with minimal transient torque requirement and zero steady state torque requirement was developed.

- A second generation tilting vehicle was fabricated and the proposed compound control system was successfully implemented.

Limitations
- Actuator saturation

Future work
- Replace steering system motor with at least 10 Amp motor and investigate high speed performance.
- Driver Haptic feedback.
Conclusion

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~ The End ~