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Heavy-Duty Truck Control: Short Inter-vehicle Distance Following

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Abstract: This paper presents implementation of truck longitudinal control for short distance following, which is a very difficult issue. The main difficulties are (a) low power/mass ratio; (b) time delay caused by and internal engine control and actuators like air brake; (c) Prominent disturbance during gear shifting, wind and slight road grade; To overcome those difficulties, a complicated nonlinear vehicle dynamics model has been adopted to reduce the model mismatch on one hand. On the other hand, robust stability margin is enhanced in control design phase. A reliable and precise distance measurement is critically required for automated vehicle following. This has been achieved by filtering and fusing both Doppler radar and laser radar with Kalman filter. Experimental work with two trucks shows that this approach is effective. Two heavily loaded trucks are used for constant inter-vehicle distance following test. The controller performance is good even for $3[m]$ inter-vehicle distance. Although, there are only two trucks tested, there is still a string stability problem because the leader truck is following a reference speed trajectory. The practical string stability study in previous work still apply. Experimental work has been presented.

1 Introduction

Based on the hardware structure of heavy duty trucks [2, 3, 4], previous work have considered in detail the modeling and longitudinal control design for a single automated truck [5, 6]. A complicated model is adopted there, which include: turbo-charged diesel engine, torque converter, transmission, and braking system (engine brake, transmission retarder and pneumatic brake). Engine braking effect, which is caused by the mismatch between engine speed and wheel speed when fuel is released and drive-line is engaged, is natually unified with Jake (compression) brake effect as a special case. The structure of the controller can be divided into upper level control and lower level control. Upper level control uses sliding mode control to generate desired engine/brake torque from desired vehicle acceleration. Lower level control is divided into two branches: (a) Engine Control: From positive desired torque to desired fuel rate (or Torque Control Command). In the case of former, using a static engine mapping is used, which captures the intrinsic dynamic performance of the turbo-charged diesel engine; (b) Brake control is to generate, from negative desired torque, to Jake-Brake-on time period, applied pneumatic brake pressure, and applied voltage of transmission retarder. Such a complicated model has been validated by using closed-loop control of a single vehicle to track a pre-defined reference speed trajectory [6].

This paper is to report the research and experimental work in longitudinal control of two or more trucks, which is basically short inter-vehicle distance following with radar/lidar distance sensing and wireless communication.

The prominent difference between the controller of one vehicle and that of multiple vehicle following is the *string stability.* As discussed in [7], the biggest enemy for string stability is *time lag* and *pure time delay* caused by sensors and actuators. Truck hardware related to longitudinal control is very complicated with large time delays [6, 10]. For Freightliner Century trucks, time lag can be as large as $0.3[s]$. Pure time delay for engine input-to-torque-production can be as large as $0.3[s]$; For braking system, transmission retarder: $0.5[s]$; Air brake: $0.6[s]$; Engine brake: $0.15[s]$. The synthetic approach in [7] is used to guarantee the practical string stability [7], and the stability and performance the following vehicle.

Basic Notations

$x_i(t)$ or simply $(x_i\ )$ – position of vehicle i in longitudinal direction. All the vehicles are with respect to a inertia frame.

$v_i(t), a_i(t)-$ speed and acceleration of vehicle i

$h_{p1}-$ time delay for obtaining front range

$h_{p2}-$ time delay for obtaining preceding vehicle's speed and acceleration

h_l- time delay for on-car sensor measuring and for communication system to pass the leader vehicle's distance, speed and acceleration to other vehicles

L_i is the desired inter-vehicle distance with vehicle length accounted for

$l-$ subscript for the leader vehicle

$M-$ vehicle mass

$\theta-$ road grade

$T_{des}-$ desired torque from upper level control

$T_{jk\_i}-$ engine Jake brake torque when i cylinder is on, $(i = 0, 2, 4, 6)$

$T_b^{(des)}-$ desired brake torque

$T_{rtd}^{(des)}-$ desired transmission retarder torque

Due to page limit, other notations, if not listed, are referred to [6].

2 Control Actuation

Due to the internal control system structure of Century Freightliner, brake (including Jake brake, transmission retarder and air brake) control and engine control are not directly accessible. Instead, it is necessary to send the control command (properly scaled) from J-1939 Bus to corresponding *Control Modules*.

2.1 Upper Level Control

Let

$$\begin{aligned} x_e &= x_{pre} - x \\ v_e &= v_{pre} - v \\ a_e &= a_{pre} - a \end{aligned}$$

Suppose the desired inter-vehicle distance is $L = const$. The sliding surface is chosen

$$s = v_e + k_1 (x_e - L), \; k_1 > 0$$

From any sliding reachability condition $\dot{s} = -\gamma(s) = -\lambda s$ [6], the desired torque T_{des} can be solved out as

$$T_{des} = \frac{\bar{I}(\lambda s + k_1 v_e + a_{pre})}{r_d r_g} + \frac{(r_d T_{rtd} + T_b + F_a h_r + F_r h_r + M g h_r \sin\theta)}{r_d r_g} \quad (2.1)$$

which generates the torque control command.

2.2 Lower Level Control

Due to internal engine control, $T_{des}(> 0)$ is directly fed into the ECM (Engine Control Module). Detailed brake control design has been presented in [6]. The main logic to coordinate the EBS (Electronic Braking System - air brake), Jake brake and transmission retarder is to use engine brake with the highest priority, then the transmission retarder. Leave the air brake only used in braking to stop or in emergency cases. Suppose the total desired braking torque on all wheels are T_{brk_total}.

A variable structure braking system control strategy has been implemented as follows.

If $T_{brk\_total} \le T_{jk\_0}$, no pneumatic brake nor jake brake is necessary but throttle is released.

If $T_{jk\_0} < T_{brk\_total} < T_{jk\_2}$, No jake brake

$$T_b^{(des)} + T_{rtd}^{(des)} = T_{brk\_total} - T_{jk\_0}$$

If $T_{jk\_2} \le T_{brk\_total} < T_{jk\_4}$, Jake brake with 2 cylinder *ON* and

$$T_b^{(des)} + T_{rtd}^{(des)} = T_{brk\_total} - T_{jk\_2}$$

If $T_{jk\_4} \le T_{brk\_total} < T_{jk\_6}$, Jake brake with 4 cylinder *ON* and

$$T_b^{(des)} + T_{rtd}^{(des)} = T_{brk\_total} - T_{jk\_4}$$

If $T_{jk\_6} \le T_{brk\_total}$, Jake brake with 6 cylinder *ON* and

$$T_b^{(des)} + T_{rtd}^{(des)} = T_{brk\_total} - T_{jk\_6}$$

3 String Stability

3.1 String Stability in Longitudinal Control

Let the distance, speed and acceleration tracking error are the following respectively,

$$\begin{aligned} \varepsilon_i(t) &= x_i(t) - x_{i-1}(t) + L_i \\ \dot{\varepsilon}_i(t) &= v_i(t) - v_{i-1}(t) \\ \ddot{\varepsilon}_i(t) &= a_i(t) - a_{i-1}(t) \end{aligned}$$

$E_i(s)$ is the Laplace transformation of $\varepsilon_i(t)$. $\|.\|_1$ and $\|.\|_\infty$ are the L_1 and H_∞ norm respectively. $G(s)$ is the transfer function of the closed-loop dynamics $g(t)$ of subsystem i, which is the same for each vehicle. Then

$$G(s) = \frac{E_i(s)}{E_{i-1}(s)} \quad (3.1)$$

The string stability for a platoon of n vehicles requires that

$$\|\varepsilon_1\|_\infty \le \|\varepsilon_2\|_\infty \le ... \le \|\varepsilon_n\|_\infty$$

From linear system theory

$$\begin{aligned} \|\varepsilon_i\|_\infty &\le \|g(t)\|_1 = \int_0^\infty |g(\tau)| \, d\tau \\ \|g * \varepsilon_i\|_\infty &\le \|g(t)\|_1 \|\varepsilon_i\|_\infty \\ \|G(s)\|_\infty &\le \|g(t)\|_1 \end{aligned} \quad (3.2)$$

Thus the inter-connected system is string stable if $\|g(t)\|_1 < 1$ and string unstable if $\|G(s)\|_\infty > 1$. To practically check it, one needs to evaluate $\|g(t)\|_1$.

Because it is feedback linearizable, it is sufficient to use the following simplified model for string stability analysis.

$$\begin{aligned} \dot{x}_i &= v_i \\ \dot{v}_i &= u_i \end{aligned} \quad (3.3)$$

where u_i is the synthetic force.

Longitudinal control design for achieving string stability in truck following is extremely challenging. The key issue is to achieve maximum string stability margin by (a) Maximally reducing model mismatch; (b) Maximally reducing time delay in sensor data filtering; (c) Maximizing *string stability margin* of the controller on each individual vehicle by proper gain choice.

Let the sliding surface be defined as

$$\begin{aligned} S_i \;=\;& \alpha \dot{\varepsilon}_i + \alpha q \varepsilon_i + (1-\alpha)(v_i - v_l) + \\ & (1-\alpha) q \left(x_i - x_l + \sum_{j=2}^{i} L_j \right) \end{aligned}$$

where $\alpha \in [0, 1]$ is the interpolation parameter. Two extreme cases are: $\alpha = 1$ which means that each vehicle follows the preceding vehicle only and no lead vehicle information is used; $\alpha = 0$ which implies that each vehicle follows the leader vehicle only. However, the most interesting cases correspond to $0 < \alpha \le 1$.

If the following sliding reachability condition

$$\dot{S}_i = -\lambda S_i$$

is used for vehicle i, with $\lambda > 0$, the controller (synthetic force) is solved out as

$$u_i^{(d)} = \alpha\, \ddot{x}_{i-1} + (1-\alpha)\, \ddot{x}_l - \alpha(q+\lambda)\, \dot{\varepsilon}_i - \alpha\lambda q \varepsilon_i - (1-\alpha)(q+\lambda)(v_i - v_l) - \lambda q\,(1-\alpha)\left(x_i - x_l + \sum_{j=2}^{i} L_j\right) \quad (3.4)$$

The design parameters (q, λ, α) are to be chosen such that

(a) The closed loop controller for each vehicle is stable;

(b) The overall system which is composed of finite number of inter-connected similar sub-systems is string stable.

3.2 String Stability and Time Delays

A first order filter is inserted to represent the effect of time lag as

$$\tau\, \dot{u}_i + u_i = u_{id}$$

With the pure time delay taken into consideration, the error dynamics for the feedback linearized model is

$$\begin{aligned} \tau \frac{d^3 \varepsilon_i}{dt^3} + \ddot{\varepsilon}_i &= u_i^{(d)} - u_{i-1}^{(d)} \\ &= -\alpha(q+\lambda)\, \dot{\varepsilon}_i - \alpha\lambda q \varepsilon_i - \lambda q\,(1-\alpha)\, \varepsilon_i \\ &- (1-\alpha)\,(q+\lambda)\,(v_i(t) - v_{i-1}(t)) + \alpha\, \ddot{x}_{i-1}\,(t - h_{p2}) \\ &+ \alpha(q+\lambda)\left(\dot{x}_{i-1}\,(t-h_{p2}) - \dot{x}_{i-2}\,(t-h_{p2})\right) \\ &+ \lambda\alpha q\,(x_{i-1}(t-h_{p1}) - x_{i-2}(t-h_{p1})) - \alpha\, \ddot{x}_{i-2}\,(t-h_{p2}) \end{aligned}$$

Using Laplace transformation on both side to get

$$G(s) = \frac{E_i(s)}{E_{i-1}(s)} = \frac{\lambda\alpha q e^{-h_{p1}s} + \alpha s e^{-h_{p2}s}\,(s + (q+\lambda))}{\tau s^3 + s^2 + (q+\lambda)\, s + \lambda q} \quad (3.5)$$

It has been shown that, if the leader vehicle information is properly used for the following vehicle by properly choosing α in controller synthesis, the string stability of vehicle following can be achieved [7].

Theorem. In vehicle following, if the linear control law (3.4) is used and if parameter K_P and K_I are chosen such that the transfer function $G(s)$ has simple and stable poles, then there exists α, with $0 < \alpha < 1$ such that the overall system is string stable irrespective of the time delays.

Let $G(s) = \alpha G_0(s)$. $g_0(t)$ corresponds to $G_0(s)$ in time domain.

Corollary Suppose that $s_i = -\sigma_i + j\eta_i$ with $\sigma_i > 0 (i = 1, 2, 3)$. Then M can be estimated as

$$\begin{aligned} |g_0(t)| &\leq M \\ &= \frac{1}{\tau}\left[\left|a^{(1)}\right| e^{\sigma_1 h_{p1}} + \left|a^{(2)}\right| e^{\sigma_2 h_{p1}} + \left|a^{(3)}\right| e^{\sigma_3 h_{p1}}\right] \\ &+ \frac{1}{\tau}\left[\left|b^{(1)}\right| e^{\sigma_1 h_{p2}} + \left|b^{(2)}\right| e^{\sigma_2 h_{p2}} + \left|b^{(3)}\right| e^{\sigma_3 h_{p3}}\right] \end{aligned}$$

which provides an upper bound for $\alpha < \frac{1}{M}$.

This paper will show how these results are used for the control of the platooning of Heavy-Duty Trucks and how to deal with mass dominant problem. Test results will be reported.

4 Other Implementation Issues

4.1 Measurement and Data Fusion

To achieve an accurate and reliable distance measure is critical for automated vehicle short distance following. As redundant sensors, a Doppler radar, Eaton Vorad (EVT-300) and Denso Lidar are used for this purpose. The characteristics of those systems are listed in Table 1.

Table 1

	$NENSO\ Lidar$	$EVT-300$
$Meas.\ principle$	$Distance\ based$	$Relative\ speed$
$No.\ of\ tracks$	8	7
$Effective\ range$	˜150[m]	˜120[m]
$View\ angle$	±20[deg]	±6[deg]
$Azimuth\ resol.$	0.01[deg]	0.1[deg]
$Longitude\ resol.$	0.01[m]	0.2˜2.0[m]
$Weather\ effect$	$Severe$	$Small$

The following algorithms are used for signal processing and data fusion.

1. Target Association

The main problem for vehicle following using radar is to detect and track the target vehicle in the front. The controller requires to focus on distance measurement and estimation. To track the main target, i.e. the front vehicle, different laser beans may be used by lidar. Radar tracking may also change the target ID during tracking. Besides, radar distance will drop to zero when relative speed is or nearly zero. These characteristics determines that t*arget association* techniques are necessary. There is a difference between lidar and radar for target association which is based on their measurement principle.

Algorithm for radar target association: Let $range[I]$, $rate[I]$, and $az[I]$, $I = 1, 2, ...7$ denote radar distance, relative speed and azimuth measurement. $track\_ID$ denote the track number for the front vehicle.

Step 1. To choose initial track: For $J = 1, 2, ...7$, if $range[J] > 1.0$ and $range[J] < 100.0$ then $track\_ID = J$. If there are more than one track number satisfy these conditions, then using smallest one as the most likely target tracking.

Step 2. Target association: For radar, start from the initial track. At each step, let $rate[track\_ID]$ and $az[track\_ID]$ represent the detected front vehicle range and azimuth respectively. For sufficiently small parameter $\varepsilon_1, \varepsilon_2 > 0$, if

$$\begin{gathered} |rate[track\_ID] - rate[J]| = \min_i\{|rate[track\_ID] - rate[i]|\} \\ |az[track\_ID] - az[J]| = \min_i\{|az[tack\_ID] - az[i]|\} \\ |rate[track\_ID] - rate[J]| \leq \varepsilon_1 \\ |az[track\_ID] - az[J]| \leq \varepsilon_2 \end{gathered}$$

then , $range[J]$, $rate[J]$ and $az[J]$ are considered as the new measure of the track of the front target.

For single target tracking, this algorithm is reasonable. For multiple target tracking, the un-used measure should be put into new tracks and the above process is to be carried for each track established.

Step 3. Set $track\_ID = J$ and go to the *Step 2.* If at least one of the last two conditions are violated, then a measurement error will be reported which may indicate that the radar target tracking has a problem.

For lidar, the above algorithm still apply except that, (a) the total number of track is 8; (b) The rate is changed to longitudinal distance and az is changed to lateral distance. The choice of parameters depends on design requirement.

2. Signal Processing

For both lidar and radar distance measurement in the established tracking, digital filters [8] are used for smoothing the distance measures. Particularly, the following filters are used:

(a) Recursive type:

$$\overline{x}_n = \lambda x_n + (1-\lambda)\overline{x}_{n-1}$$

(b) Low pass filter:

$$\begin{aligned} x_1(n) &= 0.4320x_1(n-1)-0.3474x_1(n-1)+0.1210rg_m(n) \\ x_2(n) &= 0.3474x_1(n-1)+0.9157x_1(n-1)+0.0294rg_m(n) \\ y(n) &= 0.4984x_1(n-1)+2.7482x_2(n-1)+0.0421rg_m(n) \end{aligned}$$

where $x_1(n), x_2(n)$ are filter state variables, $rg_m(n)$ is range measure at time n. $y(n)$ is filtered range at time n.

The following figure shows the radar raw data and filtered data after using the above filter.

Fig.

Lower: raw range and range-rate; Upper: filtered range and range rate

3. Data Fusion

The purpose for data fusion is to achieve a more reliable and accurate measure by means of sensor redundancy. Due to the characteristics of the two types of distance sensors, their measurement are complementary in some sense. The following three techniques are used in data fusion of radar and lidar.

(a) Using lidar distance measure to compensate for radar distance measure when relative vehicle speed is zero. In this case, radar measure will drop to zero while lidar still have a good measurement if the weather is reasonable. It is simply to use the average of previous step radar measure and current lidar measure to replace the lost radar measure. (b) If one set report error status, the measure naturally shift to the other. (c) A Kalman filter is used to fuse those two distance measures in normal cases [1].

Let $y_L(n)$, and $y_R(n)$ denote the filtered lidar range and radar range respectively at time step n; Let $y_{LR}(n)$ denote the Kalman filter estimation of combined radar and lidar signal at time step $(n-1)$. The Kalman filter is constructed as the following "predictor-corrector" structure:

$$\begin{aligned} \overline{x}(n) &= \frac{\sigma^2_{y_L(n)}}{\sigma^2_{y_L(n)}+\sigma^2_{y_R(n)}} y_R(n) \\ y_{LR}(n) &= \overline{x}(n) + K(n)\left[y_L(n)-\overline{x}(n)\right] \\ K(n) &= \frac{\sigma^2_{y_R(n)}}{\sigma^2_{y_L(n)}+\sigma^2_{y_R(n)}} \end{aligned}$$

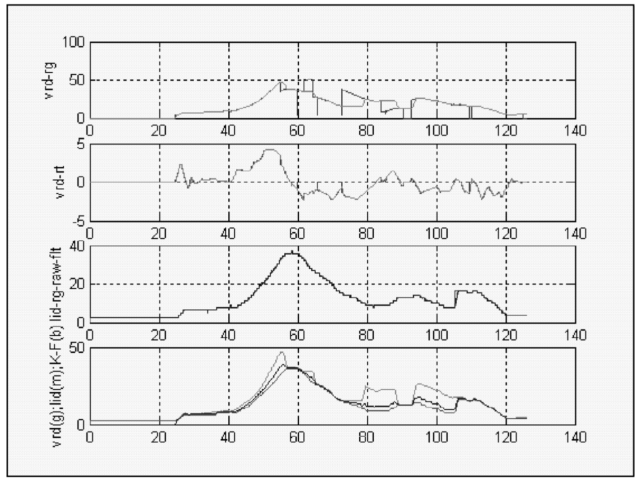

Figure 1: Filtering and fusion of radar and lidar distance signals

where $\sigma^2_{y_L(n)}, \sigma^2_{y_R(n)}$ are variance of lidar and radar distance measurement respectively.

The following figure shows the filtering and fusion of radar, lidar distance measurement. The following notations are sued in the figure: vrd_range: Eaton Vorad radar rage; vrd_rt: Eaton Vorad radar rage rate; lid_rg: Lidar range flt; filtered K-F: Fused distance using Kalman filter.

Explanation of the figure: Upper 1st plot: red is the raw radar range data and green is filtered radar range; 2nd plot: red is the radar range rate and the green is filtered radar range rate; 3rd plot: red is Lidar range raw data and the green is filtered lidar range; The lower plot: The green is filtered radar range (corresponding the green in the 1st plot), the magenta is filtered lidar range (corresponding the blue in the 3rd plot) and the blue is the fused lidar and radar range by the Kalman filter. The abrupt change of radar range as indicated in the last plot does not affect the fused range.

4.2 Wireless Communication

802.11b wireless systems are used for inter-vehicle communication. The update rate is 20[ms]. The information passed from the leader vehicle to the following vehicles involve: vehicle speed, acceleration, pedal deflection, brake pressure, maneuver_des, maneuver_id, and fault mode;

maneuver_des: An integer to specify the desired maneuver of the vehicle assigned by the coordination layer manager;

maneuver_id: Practical maneuver the subject vehicle is doing;

fault_mode; An integer to represent different faults including: radar, lidar, communication, brake actuator, engine speed, vehicle speed, etc. For each critical component, there is a fault detect mechanism to report if they are working properly.

5 Experimental Work

In the test, the first truck is fully loaded ($M = 31795[kg]$) and the second truck is half loaded ($M = 22226[kg]$). A nearly flat test track has total length $2250[m]$. Speed range tested is: $5 \sim 55[mph]$. Inter-vehicle distance tested is between: $3 \sim 10[m]$

Combined braking system tested Air brake (EBS), Jake brake and Transmission retarder. The second truck has modified EBS Box with no minimal brake value, but the first truck has a minimal brake torque which produces deceleration of $0.25[m/s^2]$. This hardware constraint behaves as a prominent disturbance and affects the performance somehow.

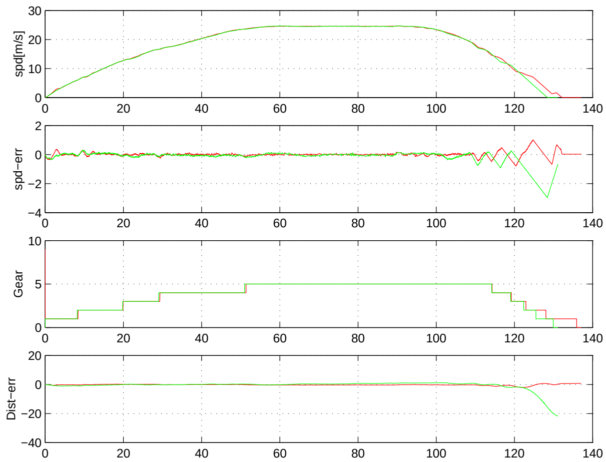

Figure 2: High speed test: Max speed 55[mph], follwing distance 6[m]

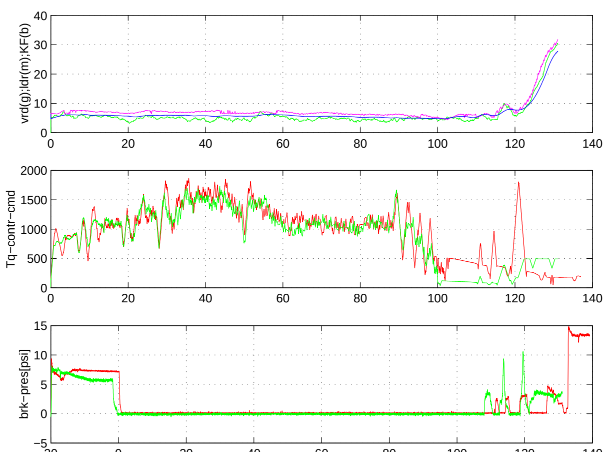

Figure 3: High speed test: Max speed 55[mph], follwing distance 6[m]

Maximum acceleration tested
$a = 0.55[m/(s^2)]$ when $v = 2.0[m/s]$

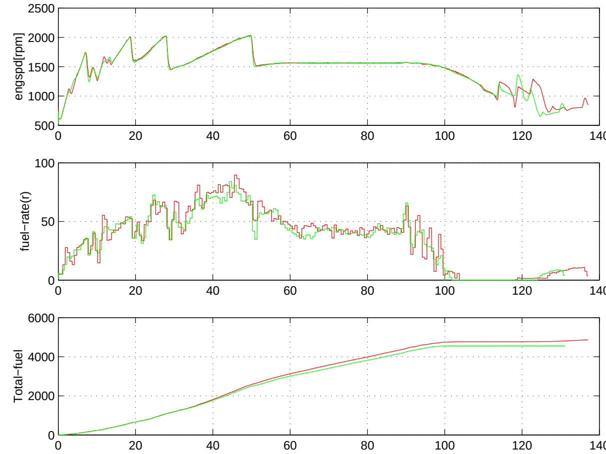

Figure 4: High speed test: Max speed 55[mph], follwing distance 6[m]

$a = 0.24[m/(s^2)]$ when $v = 14.0[m/s]$
$a = 0.06[m/(s^2)]$ when $v = 25.0[m/s]$

Maximum deceleration range tested $0.45 \sim 0.9[m/(s^2)]$. For safety, the following distance is increased when desired distance is $3[m]$ while the vehicle is braking to stop.

6 Concluding Remarks

Based on the modeling and control design in previous work [5, 6], this paper presents the implementation issues of longitudinal control of automated trucks for short distance following. Research results for practical string stability discussed in [7] is used here, which takes into consideration the time delays caused by sensors and actuators. The remaining issue for vehicle following are: distance measurement and estimation, wireless communication. Linear filter and Kalman filter are used for filtering and fusion of radar and lidar data in real-time. Although, there are only two trucks tested, considering that the first truck is following a reference trajectory, there is still a string stability problem. Extensive test has been done, which involves different following distance between $3 \sim 10[m]$, different acceleration and deceleration, and different maximum speed. Results show that the performance of the controller is good.

Work in this paper will be extended to three or more trucks in the future.

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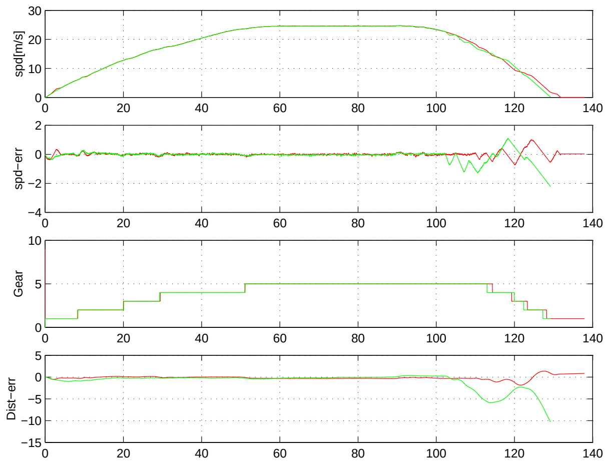

Figure 5: High speed test: Max speed 55[mph], follwing distance 3[m]

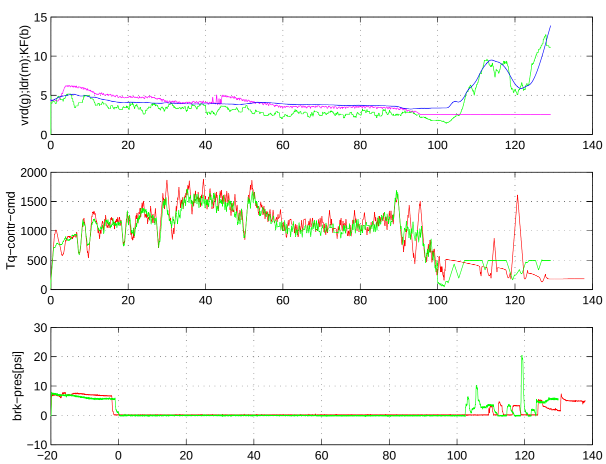

Figure 6: High speed test: Max speed 55[mph], follwing distance 3[m]

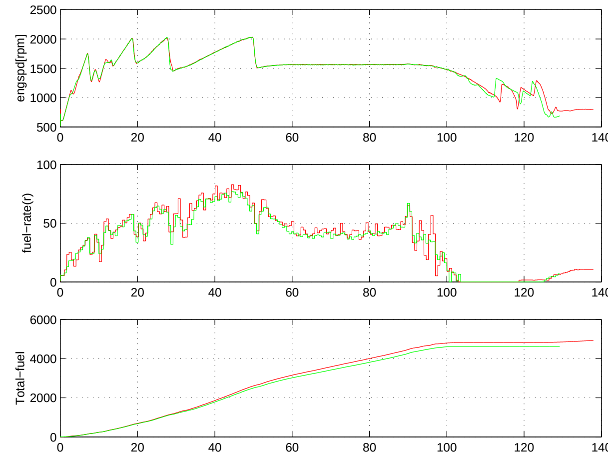

Figure 7: High speed test: Max speed 55[mph], follwing distance 3[m]

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