Using Lead Vehicle Response to Generate Preview Functions for Active Suspension of Convoy Vehicles

Hadi Adibi asl, Geoff Rideout

Abstract—Improving ride quality and active safety systems of convoy vehicles (vehicles traveling with close following distances on a specified path) can reduce fatigue and injury in military vehicle deployments and intelligent vehicle highway systems. A form of preview-active suspension control to improve convoy vehicle ride quality is proposed, wherein dynamic response of the lead vehicle is used to generate feed forward preview control gains in addition to feedback control gains for the follower vehicle suspensions. In contrast to conventional preview control with look-ahead sensors that can be expensive and unreliable, the tire deflection of the lead vehicle is estimated with a Kalman filter and used to generate road profile information for the preview controller of the followers. A virtual convoy, composed of a lead vehicle with active suspension system, and a follower vehicle with preview-controlled active suspension, is developed in MATLAB and SIMULINK [18]. The results show improved ride comfort and road holding of the follower vehicle with the novel preview approach compared to the lead vehicle with conventional active suspension. Moreover, the power demand for the follower vehicle suspension is much less than for the lead vehicle. The road holding metric (tire deflection) was more sensitive to measurement noise than was ride quality (sprung mass acceleration); however, meaningful improvements were achieved for reasonable sensor noise levels.

I. INTRODUCTION
Convoy vehicles, a series of individual vehicles traveling in close proximity on a specified path, have been recently the subject of research, especially in military applications.

Military convoys are used to carry soldiers, weapons and army supplements (Fig. 1). Many military drivers are young and inexperienced, and driver error has caused many fatal accidents in both peacetime and wartime [1]. Also, the development of an Intelligent Vehicle Highway System (IVHS) with autonomous vehicle platoons is an active research area. Therefore, research about this topic is motivated, to enhance the safety of convoy vehicles by reducing vibration-related driver fatigue, injury, overturning, and crashing.

This paper studies the potential benefits of replacing conventional passive suspension systems with a new generation of active systems to improve ride quality and safety. The idea of using communication between lead vehicle and followers in a convoy to improve the follower’s dynamic response is the primary focus of this research. The lead vehicle thus acts as a look-ahead sensor to address practical limitations of traditional preview controlled suspensions.

A. Problem statement
Using preview information of road irregularities to generate feed forward control gains, in addition to feedback gains in active suspension systems, has known benefits [2]. As will be mentioned in Section II, implementing an active suspension system with some preview time significantly improves ride comfort by reducing body acceleration, and improves road holding by reducing tire deflection. Furthermore, the

Fig. 1 Military convoy vehicles [AP Photo/ Ali Heidar, 2003]
required actuator power demand is significantly reduced when preview is added to active suspension systems.

Conventionally, preview information is provided by placing “look-ahead” sensors in front of the front bumper of the vehicle [3]. Therefore, the road irregularities are detected just before the vehicle hits them.

Using look-ahead sensor for each vehicle in a convoy is expensive, sensors are vulnerable, and sensors can be confused when potholes are filled with water or snow. This research investigates having the lead vehicle play the role of the look-ahead sensor. The lead vehicle is subjected to the road irregularities in advance and communicates its response to the follower vehicles. The lead vehicle model outputs, which are a combination of the body, unsprung mass and suspension/tire states, will be used to estimate the road profile for followers.

B. Related research

Bender [4] is among the first authors to consider road preview information to generate active suspension forces, using single degree of freedom (DOF) quarter car models. Preview reduced both body oscillation and suspension travel compared to active suspensions without preview. Similar benefits are reported in [2,3,8] using quarter and half-car models. The effect of preview time is studied in [2,3,6,10], with preview time typically having some optimal value. Hac [2] reports reduced tire deflection due to the suspension essentially anticipating bumps and lifting the tire over.

Soliman and Crolla [6] study semi-active suspension with preview, reporting significant reduction of body acceleration peak value at resonance. Dynamic tire forces are also reduced compared to semi-active-without-preview and passive suspensions. The proposed research in this paper is based on fully-active suspension; however, using semi-active suspensions for convoys would reduce cost and complexity while retaining many of the benefits reported in Section III. Application to semi-active suspensions will be treated in future work.

Power demand in preview-active suspensions has also been reported as lower than for active suspensions by Marzbanrad et al. [9,10]. Kalman filtering was used in [10] to estimate unmeasurable states. Discussion of measurable states can be found in [10,11]. Yu and Crolla [11] designed a Kalman filter for a 2 DOF quarter car, with the best estimation resulting from measuring suspension deflection, wheel velocity and body velocity. Further, [11] showed little motivation for adaptive estimators to adjust gains in response to variation in road input and system parameters such as mass. For typical passenger cars, estimator performance was insensitive to normal variations in vehicle parameters.

Vahidi and Eskandarian [12] evaluated the effect of preview uncertainties on active suspension systems with preview time, and show the benefits of using preview information to reduce the effect of the uncertainties. Two types of uncertainties were evaluated: preview sensor noise, and possible presence of false soft objects on the surface of the road. The results showed that longer preview time can be more affected by measurement noise. Also, it was shown that in both cases the tire deflection is the state most sensitive to preview noise, while suspension deflection is least affected. Furthermore, preview sensors significantly improve body acceleration, suspension deflection, and tire deflection.

Karnopp [13] proposed a long train (convoy) model of quarter cars with two DOF. A continuous form of the convoy model was used, analogous to a fluid mechanic system, to which Lagrangian and Eulerian analysis was applied. The dynamic equations of the continuum model generated the active force value based on preceding vehicles, unlike the previous papers which used a preview function to generate feed forward gains. The evaluation was based solely on the dynamics of the system, and there was no control method applied.

C. Organization of paper

Section II develops the quarter car model, describes feedback and feedforward gains, and provides details of the preview function and estimator. The goal is to estimate road profile based on the response of a lead vehicle, and use that estimate (instead of sensor data) in a follower vehicle preview-active suspension. Section III gives simulation results, and conclusions and future work are summarized in Section IV.

II. MODEL DEVELOPMENT

A. Lead-follower model

This section presents an active suspension model with preview. The main strategy in
active-preview suspension is detecting the road irregularities some time before hitting them.

As mentioned in Section I, conventional active-preview models use sensors, which are placed some distance ahead of the front bumper, to detect road irregularities (Fig. 2).

The proposed model in this research uses the lead vehicle as a preview sensor. The states of the lead vehicle are communicated to follower(s) (Fig. 3).

A simple convoy was developed with two quarter car sub-models: lead vehicle with active suspension and follower with active-preview suspension. The model parameters are given in a later table. Quarter car states (suspension deflection, sprung mass velocity, tire deflection, unsprung mass velocity) are given in Equation 1.

\[
\bar{x} = \begin{pmatrix}
    x_s - x_u \\
    \dot{x}_s \\
    x_u - x_r \\
    \dot{x}_u
\end{pmatrix}
\]  

(1)

---

Fig. 2. Quarter car with look ahead sensor (based on [3])

Fig. 3. Schematic of lead-follower communication

The road profile must be implemented inside the preview function. The road profile function is generated based on the states of the lead vehicle, a combination of tire deflection and unsprung mass velocity (\(w(t) = \dot{x}_r(t) - \frac{d}{dt}(x_u(t) - x_r(t))\)).

Feedforward and feedback gains, and follower vehicle’s actuator force:

\[
u_{ff}(t) = -\frac{B^T g(t)}{R}
\]

(4)

\[
u_{fb}(t) = -\frac{B^T (Kx(t))}{R}
\]

(5)

\[
u(t) = -\frac{B^T (g(t) + Kx(t))}{R}
\]

(6)

The desired preview time \(T_P\) is the preview time that minimizes the performance index \(J\) below (see Appendix). Table I summarizes \(J\) values for various preview times.

\[
J = \frac{1}{2} \int_0^T (x^T Q_1 x + x^T R u + u^T R u) \, dt
\]

(7)

---

Table 1

<table>
<thead>
<tr>
<th>Preview time (sec)</th>
<th>Performance index</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.01</td>
<td>1446</td>
</tr>
<tr>
<td>0.05</td>
<td>1421</td>
</tr>
<tr>
<td>0.1</td>
<td>1371</td>
</tr>
<tr>
<td>0.3</td>
<td>878</td>
</tr>
<tr>
<td>0.4</td>
<td>707</td>
</tr>
<tr>
<td>0.5</td>
<td>571</td>
</tr>
<tr>
<td>0.7</td>
<td>603</td>
</tr>
<tr>
<td>1.0</td>
<td>749</td>
</tr>
</tbody>
</table>

---

B. Observer design

As mentioned in the previous section, the road profile, which is required for the preview function, is calculated based on the states of the lead vehicle. The required states are tire deflection, sprung mass velocity, and unsprung
mass vertical velocity, which must be measured or estimated.

The sprung and unsprung mass velocity (vertical velocity of the wheel, axle, and suspension system) can be measured by implementing sensors, but the tire deflection cannot be easily measured. In other words, in reality, the tire deflection is not measurable and must be estimated.

The objective of this section is to design an estimator (observer) system to estimate tire deflection of the lead vehicle, and apply it in the feed forward control gain of follower(s). A Kalman filter, or Kalman estimator, is generated for this purpose. The model is easily shown to be controllable and observable.

The schematic diagram, Fig. 4, shows the structure of the Kalman estimator used in this research.

\[
\begin{align*}
\dot{x} &= Ax(t) + Bu(t) + D[w(t) + \eta(t)] \\
y &= Cx(t) + v(t) \\
\dot{\hat{x}} &= A\hat{x}(t) + Bu(t) + L(t)[y(t) - C\hat{x}(t)]
\end{align*}
\]

Observer gains are given by

\[
L(t) = (P(t)C^T)W
\]

Where \( P \) is the solution to the following algebraic Riccati equation.

\[
AP(t) + P(t)A^T - P(t)C^TWCP(t) + DVD^T = 0
\]

Input and measurement noise variance matrices are, respectively, \( V = E(\eta(t)\eta(t)^T) \), \( W = E(v(t)v(t)^T) \), \( E(\eta(t)) = E(v(t)) = 0 \).

\( E(X) \) represents the expected value function. Noise parameters are determined following [11], wherein sensor error and RMS values of measurements are related to Gaussian white noise standard deviation \( \sigma \). Noise intensities \( \sigma^2 \) are used in the input and measurement noise intensity matrices \( V \) and \( W \). See parameter Table II below. The inputs to the plant model in Figure 4 are road profile \( w(t) \) and actuator force \( u(t) \), which is calculated based on the Linear Quadratic (LQ) method [15]. The output of the plant block is \( y(t) \), the measurement vector. In the proposed model, the measurement vector \( y = Cx \), where \( C = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \), contains suspension deflection, sprung mass velocity, and unsprung mass velocity. The measurement error is simulated by Gaussian white noise \( v(t) \). The output of the estimator is an estimated state vector that includes tire deflection, which is used to generate a road profile. The road profile is an output of the lead vehicle submodel, and is transferred in the form of data arrays to the preview function of the follower vehicle submodel. Feedforward gain is calculated by interpolating the data from the estimated road profile. The estimator block diagram is shown in Fig. 5.

![Fig. 4 Kalman estimator schematic](image)

As can be seen in the diagram, the upper block represents the system (plant) (Eqn 8). Equation 9 is the estimator dynamic equation.

![Fig. 5 Observer block diagram.](image)

### III. SIMULATION RESULTS

Table II lists model parameters. Simulations were carried out for a discrete bump road profile with roughness (input noise). The ride quality variables are compared for the lead (active) and the follower (active preview) in both time and frequency domains. The ability of the lead vehicle to estimate the road profile is also assessed. The road profile is a single bump with height of 0.2 m with Gaussian white noise.
roughness (Fig. 6 and Fig. 7). Figure 6 shows both actual and estimated road profile, demonstrating the effectiveness of the estimator. The roughness coefficient ($G_0$) and vehicle forward velocity ($U_0$) in Table II are used to calculate input noise deviation (variance) parameter as follows: $\sigma^2 = 2\pi G_0 U_0$.

![Fig. 6 Estimated road profile](image)

![Fig. 7 Road roughness (input noise)](image)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sprung mass ($M_b$)</td>
<td>100 kg</td>
</tr>
<tr>
<td>Unsprung mass ($M_w$)</td>
<td>10 kg</td>
</tr>
<tr>
<td>Suspension damping ($C_b$)</td>
<td>100 N/(m/s)</td>
</tr>
<tr>
<td>Suspension stiffness ($K_b$)</td>
<td>10000 N/m</td>
</tr>
<tr>
<td>Tire stiffness ($K_t$)</td>
<td>100000 N/m</td>
</tr>
<tr>
<td>Preview time ($T_p$)</td>
<td>0.5 sec</td>
</tr>
<tr>
<td>Roughness coefficient ($G_0$)</td>
<td>5e-6 (m$^3$/cycle)</td>
</tr>
<tr>
<td>Vehicle speed ($U_0$)</td>
<td>20 (m/s)</td>
</tr>
<tr>
<td>Deviation of noise for suspension deflection ($\sigma$)</td>
<td>1e-8</td>
</tr>
<tr>
<td>Deviation of noise for sprung mass velocity ($\sigma$)</td>
<td>1e-6</td>
</tr>
<tr>
<td>Deviation of noise for unsprung mass velocity ($\sigma$)</td>
<td>1e-6</td>
</tr>
</tbody>
</table>

Table II

MODEL PARAMETERS AND VALUES

As shown in Fig. 8, the body acceleration is significantly improved by the suspension system with preview information from the lead vehicle’s road profile estimator. However, the measurement noises slightly disturb the follower response. The suspension deflection is slightly improved, especially in the second peak value (Fig. 9). As can be seen in this figure, the suspension deflection is not significantly affected by the measurement noises, in comparison with body acceleration and tire deflection.

In Fig. 10, the tire deflection is improved at its peak value, but it is strongly affected by measurement noise.

The power demand is significantly reduced in the follower vehicle (Fig. 11), which verifies that using some preview time in an active suspension system can significantly reduce power demand [2, 9].

![Fig. 8 Body acceleration (lead vs. follower)](image)

![Fig. 9 Suspension deflection (lead vs. follower)](image)

![Fig. 10 Tire deflection (lead vs. follower)](image)
The Fast Fourier Transform (FFT) of the autocorrelation function is used to illustrate the frequency domain results. As shown in Fig. 12 and Fig. 14, the body acceleration and tire deflection are significantly improved in the frequency domain. However, the suspension deflection is only slightly improved (Fig. 13).

Overall, the use of the lead vehicle as a preview sensor effectively improves ride quality, as indicated by body vertical acceleration. Peak tire deflection and roadholding are improved, but are noisy using the current estimator. Roadholding benefits are nonetheless meaningful if the preview capability of the system is only used to reduce the effect of unforeseen discrete bumps encountered by the lead vehicle, rather than general road roughness. Closely spaced follower vehicles would likely not be able to avoid such a discrete road event.

It was assumed that all vehicles have identical speed and constant following distance, and that signals are communicated instantly from lead to follower. Inclusion of a driver model and cruise control for follower vehicles will introduce uncertainty in the time at which preview signals are acted on by the follower's suspension. Future work will study the robustness of the preview suspension to errors in predicting when upcoming bumps will occur, and incorporate more realistic limitations on the communication of information.

IV. CONCLUSION

The main goal of this paper is to investigate active suspension system issues specifically applicable to convoy vehicles, and how to improve vertical dynamics of convoy vehicles by communicating preview information, e.g. road irregularities, from lead vehicle to follower(s). For this purpose, a lead-follower quarter-car convoy model is designed, where the active and active-preview suspension systems are implemented in lead and follower models respectively.

The main contribution of this research is using the response of the lead vehicle, e.g. tire deflection, sprung mass and unsprung mass velocity, to predict the road profile for follower(s). This method suggests the possibility of improving convoy ride quality through preview control while eliminating expensive and vulnerable sensors for each vehicle. However, since measuring the tire deflection is practically impossible, the Kalman observer is used to estimate it.
The results show that the suspension variables related to improving ride comfort, such as body acceleration, are significantly reduced, and the suspension deflection is improved in the follower vehicle model with active-preview suspension system compared with the lead vehicle with active suspension system. The tire deflection and power demand were also reduced. Tire deflection reduction translates to better road holding ability, as available tire lateral force is directly related to tire normal force. Future preview-active suspension work will study the effects of delays and noise in inter-vehicle communication, and variations in following distance. Estimator design will be refined to reduce the effect of noise. Quarter car models will be extended to half- and full-car models to incorporate pitch and roll responses. Increased road holding potential is important for another planned extension of the work – preview controlled obstacle avoidance – in which lead vehicle responses in the yaw plane will be used to improve stability control and obstacle avoidance of convoy vehicles. Application to semi-active suspensions will also be investigated, to improve the attractiveness of the method in terms of cost and complexity.

ACKNOWLEDGEMENT

The authors would thank the Natural Sciences and Engineering Research Council of Canada (NSERC) Discovery Grant Program, and the AUTO21 Network of Centers of Excellence Project E301-EHV, for providing financial assistance for this research.

REFERENCES


APPENDIX

System, gain and cost function matrices [17]:

\[ A = \begin{bmatrix} 0 & -K_s/M_b & 0 & -C_s/M_b \\ -K_s/M_b & C_s/M_b & 0 & -C_s/M_b \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 \end{bmatrix} \]

\[ B = \begin{bmatrix} 0 \\ 1/M_b \\ -1/M_b \\ 0 \end{bmatrix} \]

\[ C = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 \end{bmatrix} \]

\[ D = \begin{bmatrix} 0 \\ 0 \\ -1 \\ 0 \end{bmatrix} \]

\[ Q = \begin{bmatrix} K_s^2 + r_s M_b^2 & 2C_s K_s & 0 & -2C_s K_s \\ 2C_s K_s & C_s^2 + r_s M_b^2 & 0 & -2C_s^2 \\ -2C_s K_s & -2C_s^2 & 0 & C_s^2 \end{bmatrix} \]

\[ N = \begin{bmatrix} 1/M_b^2 & 0 \\ 0 & 1 \end{bmatrix}, \quad R = \begin{bmatrix} 1/M_b^2 + r_s \\ 0 \end{bmatrix} \]

\[ L = \begin{bmatrix} 453.66 & 0.0383 & 0.0037 \\ 4.5366 & 0.0395 & 0.0001 \\ 86.608 & -0.0349 & 0.0340 \\ 0.4537 & 0.0001 & 0.0030 \end{bmatrix} \]