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ANALYZING CLASSES OF MOTION DRIVE ALGORITHMS BASED ON PAIRED COMPARISON TECHNIQUES

Peter Grant
University of Toronto Institute for Aerospace Studies
4925 Dufferin St, Toronto, Ontario Canada, M3H 5T6
Ph-416-667-7726
Fax-416-667-7799
prgrant@utias.utoronto.ca

Mike Blommer
Scientific Research Laboratory
Ford Motor Company
2101 Village Rd.,
Rec R., MD 2115 SRL
Dearborn, MI 48121
Ph-313-621-8197
mblommer@ford.com

Larry Cathey
Scientific Research Laboratory
Ford Motor Company
2101 Village Rd.,
Rec R., MD 2115 SRL
Dearborn, MI 48121
313-337-5327
lcathey@ford.com

Bruce Artz
Scientific Research Laboratory
Ford Motor Company
2101 Village Rd.,
Rec R., MD 2115 SRL
Dearborn, MI 48121
Ph-313-323-0347
bartz@ford.com

Jeff Greenberg
Scientific Research Laboratory
Ford Motor Company
2101 Village Rd.,
Rec R., MD 2115 SRL
Dearborn, MI 48121
Ph-313-3238273
jgreenb2@ford.com

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ABSTRACT

High-fidelity motion-based simulators, such as VIRTTEX at Ford Motor Company, employ motion systems to provide drivers with the appropriate vestibular, proprioceptive, and tactile motion cues while driving. Since most driving maneuvers involve motions that greatly exceed a simulator's motion displacement capability, the calculated vehicle motions must be filtered before they are sent to the motion system. This filtering is implemented within the Motion Drive Algorithm (MDA). Parameters within the MDA are typically chosen to minimize errors between the calculated vehicle and simulator motions while keeping the simulator within its displacement capability. There currently does not exist a complete human motion perception model that can be used to mathematically determine the optimal values for the many parameters in a particular MDA. Thus, the best parameter set, or tuning, is usually subjectively chosen.

In a previous investigation, Paired comparison (PC) techniques were introduced in a previous investigation as a methodology for subjectively comparing the fidelity of different MDAs. These techniques are useful for tuning MDAs because humans can make very consistent and repeatable judgments when comparing two stimuli that are presented with a relatively short inter-stimulus interval. The current investigation compares the best parameter sets (as determined in the previous study) for two different classes of MDAs: a classical frequency splitter-based MDA, and a lane position MDA. The lane position MDA uses the vehicle lateral lane position to generate lateral motion of the simulator, and road curvature and speed to generate simulator low frequency roll. Three other general-purpose classical parameter sets are also compared in this investigation. These parameter sets are not tuned specifically for the maneuvers used in this study, and can be used for typical highway driving with arbitrary lane changes. The three parameter sets were also selected to have different ratios of specific force error to roll rate error. When tuning a classical algorithm for maneuvers that generate significant lateral specific force there is a trade-off between specific force error and roll rate error. The roll of the simulator is used to simulate the low-frequency component of the specific force by tilting the g-vector in the horizontal plane of the driver. Rolling the simulator quickly leads to less specific force error but to larger roll rate errors. A low-gain lane position parameter set was also compared in the current study to investigate the trade-off between cueing shape errors and scaling errors.

The well tuned, maneuver specific, classical MDA, achieved a fidelity level on par with an equally scaled lane position MDA. The general-purpose classical MDA parameter sets did not achieve the same fidelity as the identically scaled lane position MDA. The best general purpose classical MDA parameter sets with a scaling of 0.5 were preferred to the lane position MDA with a scaling of 0.3. This suggests that the shape errors of these cases are smaller than the additional scaling error associated with a scaling of 0.3. A strong effect in the trade-off between specific force error and angular rate error was not found.

NOMENCLATURE

K_y - lateral specific force gain

K_p - roll gain

K_r - yaw gain

K_M - mode switch: 0-Positional MDA;1-Classical MDA

s - Lapace operator

a - acceleration vector

g - gravity vector

f_y^V - lateral specific force in vehicle at reference point

f_y^S - lateral specific force in simulator at reference point

ω_p^V - vehicle roll angular velocity

ω_p^S - simulator roll angular velocity

ω_r^V - vehicle yaw angular velocity

ϕ_s, θ_s, ψ_s - simulator roll, pitch and yaw Euler angles

L_{IS} -simulator body frame to inertial frame transformation matrix

R - simulator body angular velocity to Euler rate transformation matrix

ω_{hpy} -lateral 2nd-order high-pass break freq.

ς_{hpy} -lateral 2nd-order high-pass damping

ω_{lpy} - lateral 2nd-order low-pass break freq.

ς_{lpy} -lateral 2nd-order low-pass damping

ω_{by} - lateral 1st-order low-pass break freq.

ω_{hpp} - roll 2nd-order high-pass break freq.

ς_{hpp} -roll 2nd-order high-pass damping

ω_{hpr} - yaw 2nd-order high-pass break freq.

ς_{hpr} -yaw 2nd-order high-pass damping

$\dot{\phi}_{LIM}$ - cross-feed rate limit

$\ddot{\phi}_{LIM}$ -cross-feed acceleration limit

INTRODUCTION

High-fidelity motion-based simulators, such as VIRTTEX at Ford Motor Company, employ motion systems to provide the vestibular, proprioceptive, and tactile motion cues to the driver. Since most driving involves motions that greatly exceed a simulator's motion displacement capability, the calculated vehicle motions are filtered by the Motion Drive Algorithm (MDA) before they are sent to the motion system. A large number of parameters within the MDA are selected (or tuned) to minimize errors between the calculated vehicle motion and simulator motion, while keeping the simulator commands within its displacement envelope.

Although there has been recent progress (see Hosman et al [1] for example), there still does not exist a complete human motion perception model that can be used to mathematically determine the optimal values for the parameters within the MDA. Current motion perception error measures cannot adequately capture the severely non-linear phenomenon of false cues. The best parameter set is therefore typically determined using human-in-the-loop subjective tuning or evaluation.

Paired comparison (PC) techniques were introduced by Grant et al [2], as a methodology for subjectively comparing the fidelity of different MDAs for driving simulation. These techniques are favored, because humans can make very consistent and repeatable judgments when comparing two stimuli that are presented with a short inter-stimulus interval. The current investigation compares the best tuning conditions determined by Grant et al [2] for two different classes of MDAs: a classical frequency-based MDA, and a lane position MDA. In addition, the current study compares three different tuning strategies for a general-purpose classical parameter set as well as a low-gain lane position MDA parameter set. In this PC study, drivers make subjective evaluations between modest lane change maneuvers on a narrow straight road at constant forward speed. Although the lane position based algorithm is expected to be preferred, the strength of this preference is of interest—particularly because the classical algorithm has benefits for simulation of combined longitudinal and lateral accelerations on hexapod type motion systems. The lane position algorithm often requires a large lateral offset of the motion system when the vehicle is in the right lane, which leaves very little motion available for braking or acceleration maneuvers.

MOTION DRIVE ALGORITHM

The VIRTTEX motion drive algorithm for lateral and roll motion is shown in Figure 1. Note that it is somewhat different than originally described by Grant et al [2].

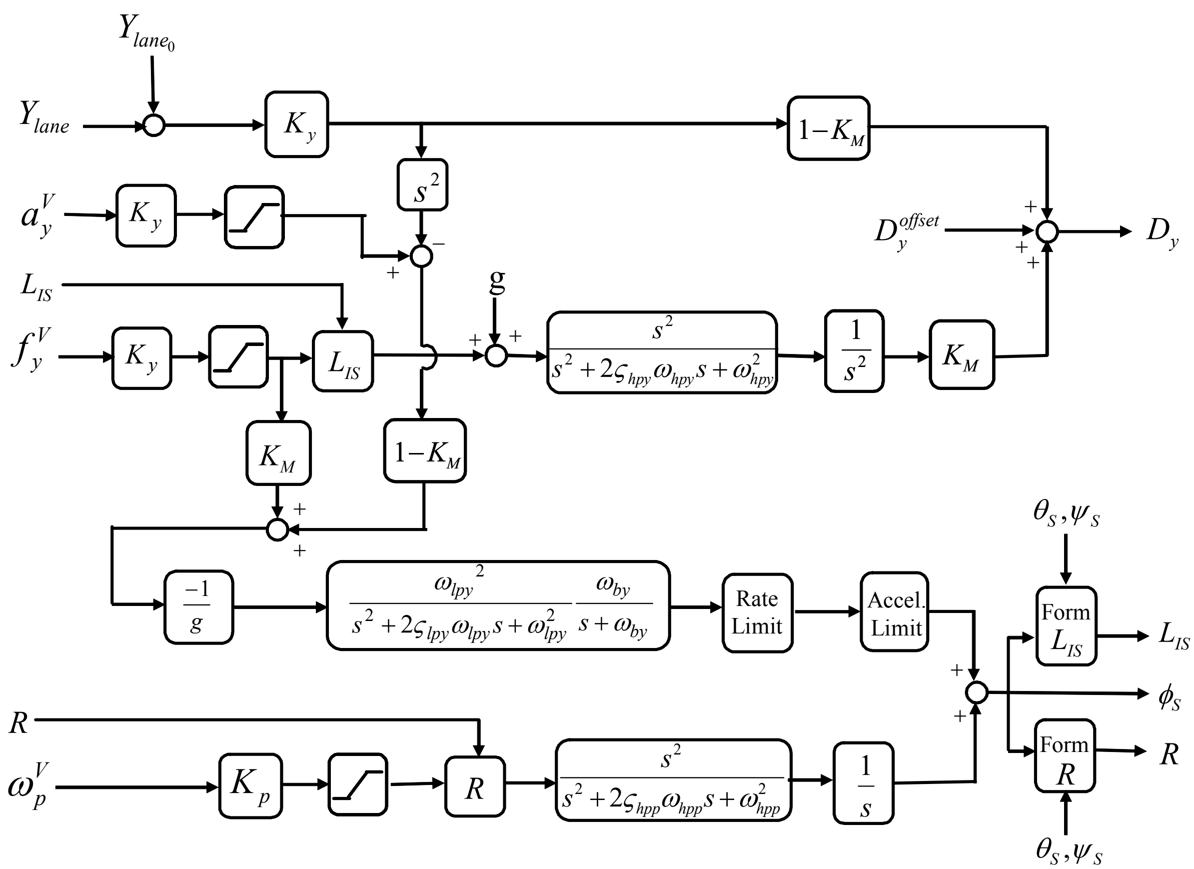

Figure 1 VIRTTEX motion drive algorithm, lateral and roll channels

When the gain, K_M, is set to zero, the MDA becomes a lane position drive algorithm. The lateral position command to the motion system is determined by scaling the lateral position of the vehicle within its lane. As shown in, the roll command to the motion system for this case is the sum of two components. The first component is derived by scaling and high-pass filtering the vehicle roll rate (ω_p^V). The second component of the roll command is a function of the difference between the lateral acceleration of the vehicle and the acceleration due to the double differentiation of lane position. This accounts for the acceleration due to roadway curvature. This acceleration difference is converted to a roll angle by dividing by –g. It is then low-passed, and rate and acceleration limited. The steady state roll angle is such that the lateral component of gravity in the simulator body frame is equal to the scaled lateral acceleration of the vehicle resulting from to roadway curvature. The low-pass filter, the roll rate and roll acceleration limiters can be used to keep the roll rate and acceleration below the driver's perception threshold.

When the gain K_M is set to one, the MDA becomes a classical frequency splitter based MDA. The input to the lateral translation channel is the lateral specific force (at the vehicle reference point) in the body carried vehicle frame (f_y^V). Specific force is what an accelerometer measures (i.e. acceleration minus the gravity vector, $a-g$). The reference point is the center of the simulator angular rotations. The specific force is scaled, transformed into the inertial frame, and then high-passed filtered to determine the lateral command to the simulator motion system. The lateral specific force also feeds into the roll command of the simulator. The lateral specific force is converted to a roll angle (by dividing by –g), low-passed filtered and then rate and acceleration limited. This low-frequency roll tilts the g-vector such that its lateral component in the simulator body frame is equal to the low-frequency lateral specific force in the vehicle body frame. This roll cross-feed reproduces the low-frequency part of the lateral specific forces and the lateral translation reproduces the high-frequency part of the lateral specific force. The sum of the high-pass and low-pass parts does not typically reproduce the scaled specific force perfectly. Since the roll cross-feed produces extraneous roll motion, the low-pass filters and limiters in the roll cross-feed are used to keep the angular rate and acceleration of the roll cross-feed below the perception threshold of the driver. In addition to the roll errors, the roll cross-feed can also produce significant lateral specific force errors if the center of the roll motion (which is at the reference point) is distant from the drivers head. The errors in specific force are equal to product of the angular acceleration error and the distance from the center of rotation. For details of the classical MDA errors and cueing response see Grant and Reid [3].

The VIRTTEX motion drive algorithm for yaw motion is shown in Figure 2. The input is yaw rate.

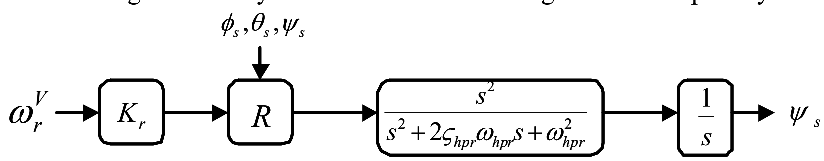

Figure 2 VIRTTEX MDA, Yaw Channel

All of the parameters within the MDA, including K_M, can be switched while driving. The parameters that are associated with only the classical MDA are switched from the current values to new values using a linear ramp of three seconds. The parameters that are associated with the lane position MDA (K_M, K_y) are switched using a non-linear ramp that is 3 times differentiable, resulting in selectable jerk and acceleration limits. The translational offset of the simulator, D_y^{offset}, must be changed between the lane position algorithm and the classical algorithm using a jerk limited, acceleration square wave.

EXPERIMENTAL SET-UP

VIRTTEX Simulator

VIRTTEX is a high-fidelity moving base simulator. VIRTTEX consists of a 24-foot diameter carbon fiber dome section mounted on top of a high performance six degrees-of-freedom hydraulic motion system. A vehicle cab is mounted inside the dome, with the driver's eye-point located at the center of the dome viewing volume. Five projectors are used to project a 180°x40° front and a 120°x25° rear image onto the inside surface of the dome. The inside surface of the dome is covered with a high-gain coating to provide a bright image at the drivers eye-point location. Cathey et al [4] describe the VIRTTEX visual system in detail.

Motion Base

The VIRTTEX motion system is a hydraulic Stewart platform with 64-inch stroke actuators. It has a lateral displacement limit of ±1.6m, a lateral velocity limit of approximately 1.5 m/s and a lateral acceleration limit of 0.6g. The yaw and roll capabilities exceed the requirements for the maneuver used for this study. For details of the motion system, see [5].

Vehicle Dynamics

A model of a 2002 Ford Taurus was used in this study. This vehicle is a full-size North American Sedan that weights approximately 3500lbs. The vehicle model is a 10-dof multi-body chassis model with a combined Pacejka tire model and relaxation length dynamics. The steering system model is described in [6]. The vehicle model was validated using vehicle test data.

Driving Maneuver

The trajectory of the maneuver used in this study is shown in Figure 3, where 0 m corresponds to the right lane, and –2.95 m corresponds to the left lane. Cones spaced 2.95m apart laterally and 3.8m

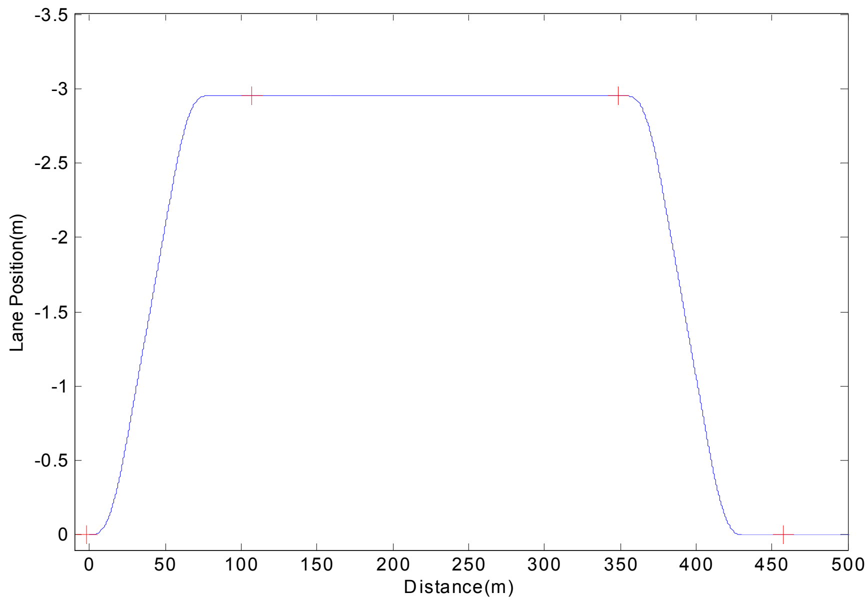

Figure 3 Driving Maneuver

apart longitudinally, delineate the maneuver. Speed control kept the vehicle forward speed at 60mph (97kmph) during the entire experiment. The lateral specific force and roll rate for the left hand lane change part of the maneuver for an idealized driver and a simplified vehicle dynamic model are shown in Figure 4 and Figure 5, respectively.

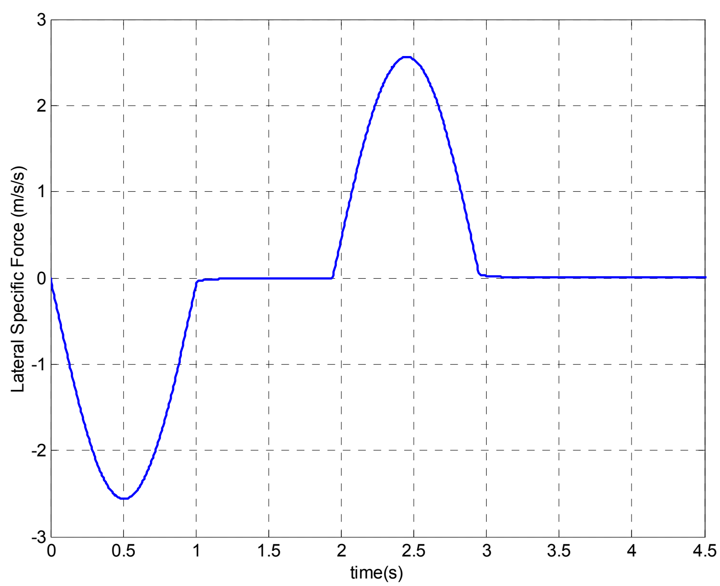

Figure 4 Specific Force for Left Hand Lane Change, Idealized Driver

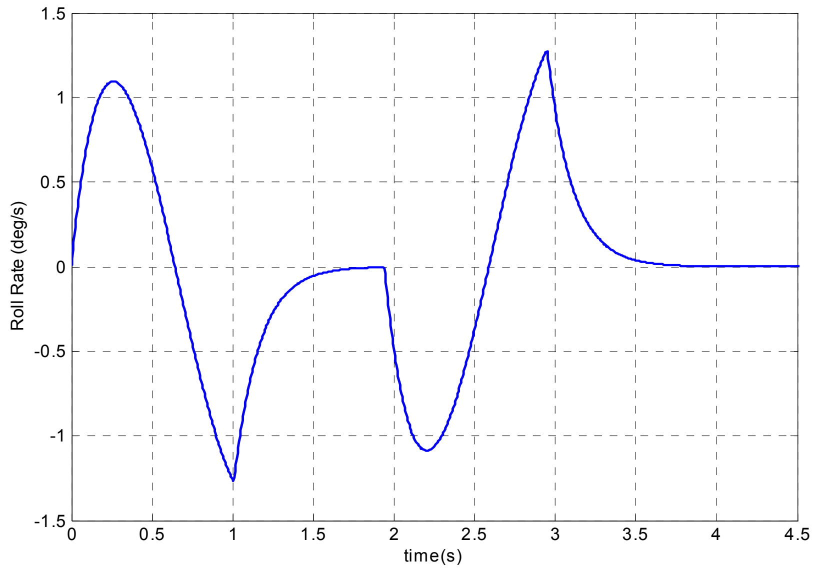

Figure 5 Roll Rate for Left Hand Lane Change, Idealized Driver

The distance between the left and right hand lane change resulted in 10 seconds between compared conditions. Ten seconds was a compromise--long enough to switch motion parameters without excessive extraneous acceleration, but short enough to allow sensitive comparisons.

This maneuver is repeated at 3000 ft (913.7 m) intervals. The left hand lane change is driven with one tuning condition and the return to the right lane is driven with a second tuning condition. The driver selects the most realistic motion tuning condition from this pair. White lines are drawn across the road at the locations indicated by the red + in Figure 3. These delineate the start and end of the motion intervals that are to be compared, thereby allowing the subjects to ignore the extraneous motion that occurs due to parameter switching between the pairs.

MDA Tuning Cases

The most realistic classical and lane position parameter sets determined in a previous PC study by Grant et al [2] were selected for comparison in the current study and are designated CA and PA. Three additional general-purpose classical parameter sets (CB, CC, and CD) were also compared in the current study. The four classical parameter sets used in [2] were highly optimized for the particular lane change maneuver used in the study; typical highway driving with arbitrary lane changes would likely lead to significant position limiting and correspondingly large motion errors. The three new classical sets are applicable to normal highway driving with moderate, arbitrary lane changes. These three classical sets were selected to study the trade-off between lateral specific force error and roll rate error. The total lateral specific force is a combination of high-passed translational motion and low-passed, rate and acceleration limited tilt. Increasing the low-pass filter break frequency reduces the specific force error because the specific force from the tilting of the g vector in the body frame will build up more quickly. This will however lead to increase in the roll rate (and roll acceleration) error. Decreasing the low-pass filter break frequency has the exact opposite effect. Case CB was chosen to balance the normalized specific force and roll rate errors. Case CC has a reduced roll rate error at the expense of increased specific force error and case CD has a reduced specific force error at the expense of the roll rate error. The final MDA case was a lane position tuning case with a gain of 0.3 (case PB). A low-gain lane position washout was selected to study the trade-off between gain error of lane position algorithms and the shape errors of the classical algorithm. All the parameter sets are shown in Table 1.

	CA Classical	CB Classical	CC Classical	CD Classical	PA LanePos	PB LanePos
K_y	0.5	0.5	0.5	0.5	0.5	0.3
K_p	0.5	0.5	0.5	0.5	0.5	0.3
K_r	0.5	0.5	0.5	0.5	0.5	0.3
ω_{hpy} (r/s)	0.32	0.4	0.5	0.2	-	-
ς_{hpy}	0.4	0.5	0.5	0.5	-	-
ω_{hpp} (r/s)	0.1	0.1	0.1	0.1	0.1	0.1
ς_{hpp}	1.0	1.0	1.0	1.0	1.0	1.0
ω_{hpr} (r/s)	1.0	1.0	1.0	1.0	1.0	1.0
ς_{hpp}	0.8	0.8	0.8	0.8	0.8	0.8
ω_{lpy} (r/s)	0.9	1.2	0.8	1.5	-	-
ς_{lpy}	1.5	1.2	1.3	1.2	-	-
ω_{by} (r/s)	2.0	8.0	4.0	8.0	-	-
$\dot{\phi}_{LIM}$ (deg/s)	4.0	4.0	4.0	4.0	-	-
$\ddot{\phi}_{LIM}$ (deg/s^2)	57	57	57	57	-	-
Ref. Pt.(m)*	1.4	1.4	1.4	1.4	-	-
$\hat{f}_y^{err}$ (m/s^2)	4	6	8	3	0	0
$\hat{\omega}_p^{err}$ (deg/s)	2.4	6	3	8	0	0

Table 1 Tuning Conditions

The last two rows in the table show the peak normalized lateral specific force shape error and the peak normalized roll rate shape error for an idealized driver and simplified vehicle dynamic model. The shape errors do not include the effect of scaling and are found from,

$$f_y^{err} = K_y f_y^V - f_y^S \quad ; \omega_p^{err} = K_p \omega_p^V - \omega_p^S$$

The error due to scaling is considered separately from the shape error because the reduction in fidelity may be of a different order [3]. The specific force shape errors are normalized by 5mg and the roll rate shape errors are normalized by 0.5 deg/s. These are the detection thresholds for a pure observer as determined by Greig [7]. This normalization allows for comparison of specific force and angular rate errors on a common scale. Although the experiment is closer to a Just Noticeable Difference (JND) experiment than an absolute detection experiment, it is reasonable to assume that the relative magnitude between the specific force and angular rate detection levels for a JND study will be similar to those found in by Greig [7]. Thus, only the relative magnitudes of the normalized shape errors can be considered.

In the previous PC study, the preferred classical tuning parameter set had a normalized roll rate error that was smaller than the normalized specific force error. The preference was not strong and there were potentially

* Distance directly below drivers head

confounding effects due to the inclusion of the extraneous motion between pairs (due to parameter switching) in the comparisons (see Grant et al [2]). The trade-off between roll rate error and specific force error was therefore re-examined in the current study, but with the addition of white lines on the roadway to indicate when motion due to the MDA tuning condition was to be evaluated. The parameter sets used in this study, for examining this trade-off, are more general-purpose tuning conditions than those used in [2]. Since the MDA was not specifically tuned for the given maneuver, the resulting motion errors are larger in the current study, thereby increasing the chances of finding significant differences between the tuning cases. The normalized specific force errors for the four classical maneuvers and an idealized driver and a simplified vehicle dynamic model are shown in Figure 6 (the dimensional specific force shape error is indicated on the right vertical axis). The normalized roll rate errors are shown in Figure 7 (note that the dimensional roll rate error is indicated on the right vertical axis).

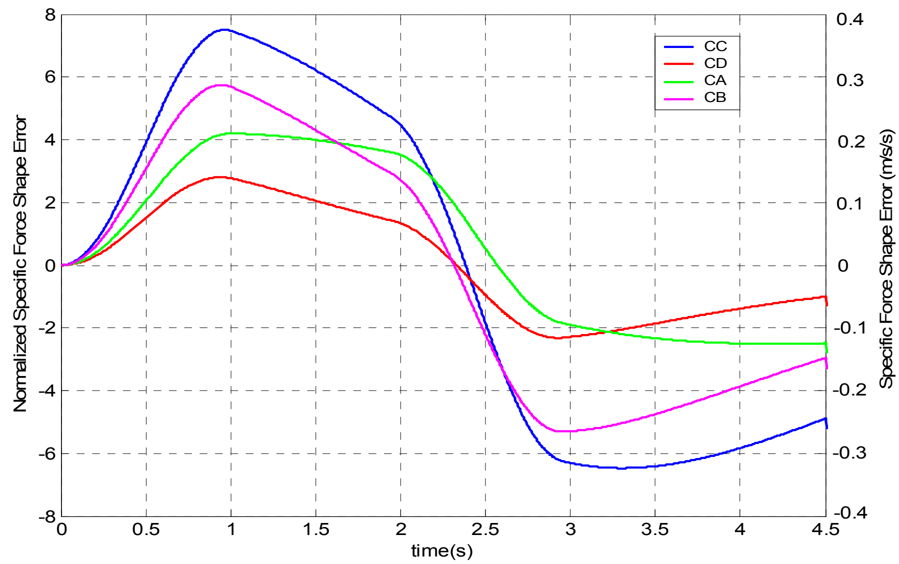

Figure 6 Normalized Specific Force Errors for Idealized Driver and Simplified Vehicle Dynamics

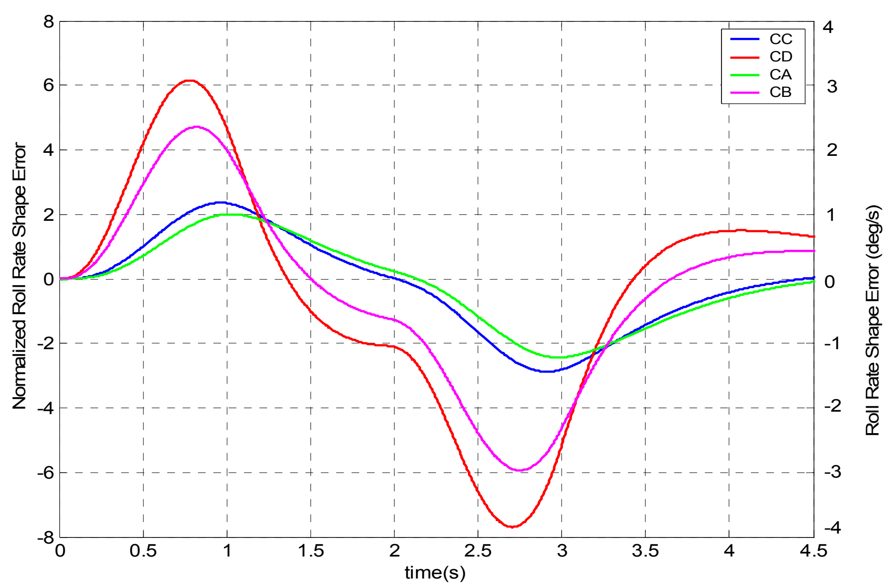

Figure 7 Normalized Roll Rate Errors for Idealized Driver and Simplified Vehicle Dynamics

Experimental Procedure

Twenty-three subjects participated in the current study. Three subjects were vehicle test drivers and twenty subjects were Ford Motor Company employees with varying degrees of test driver experience. The subjects were asked to indicate which motion condition felt more like a real vehicle. The subjects had 8 practice trials, then immediately started the experimental tests. The experiment consisted of 15 pairs repeated twice. The 15 pairs were randomized then repeated with the first and second tuning conditions reversed. The entire drive consisted of 38 trials and took approximately 20 minutes.

RESULTS AND DISCUSSION

Driving Performance

Before analyzing the paired comparison data, it is important to examine the actual motion experienced by the drivers. If the maneuver is driven significantly different from the idealized driver, then the various tuning conditions will not generate the normalized errors given in Table 1. Additionally if the drivers are not repeatable in their driving this could reduce their ability to distinguish subtle differences between pairs. The lateral specific force for the idealized driver and the 15 right hand turn trials for subject 8 is shown in Figure 8. Plots for the other subjects are generally quite similar. From the figure it can be seen that the driver was very repeatable in their driving performance, and it is also clear that they did not drive like the idealized driver.

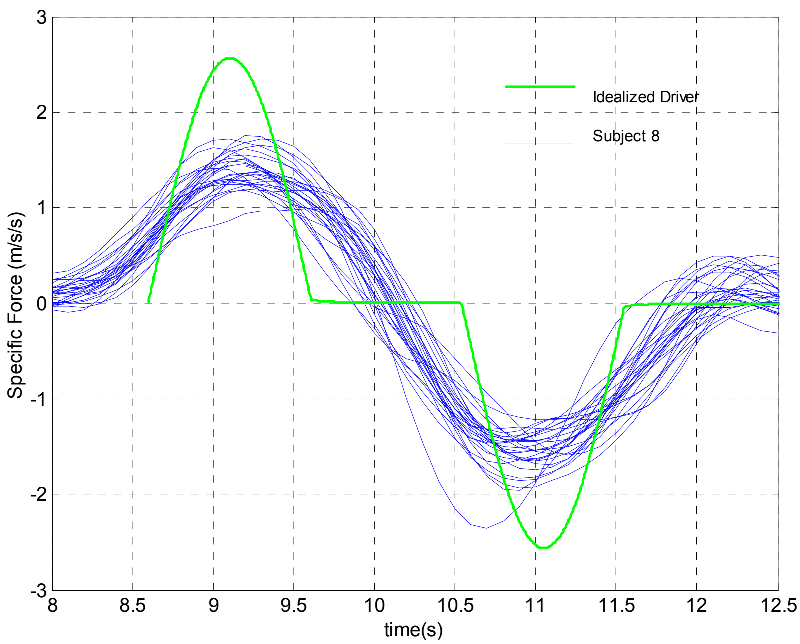

Figure 8 Lateral Specific Force for Subject 8

The difference between the idealized driver and subject 8 is typical for all drivers. Rather than perform two distinct steering inputs with a straight section between, the drivers generated a smooth, continuously changing steering input. This resulted in reduced peak lateral specific force and roll rate relative to the idealized maneuver. The resulting normalized errors for subject 8 right hand turns for case CA are shown in Figure 9 . Although the error shapes are somewhat different from for those shown in Figure 6 and Figure 7 the peak errors are almost equal.

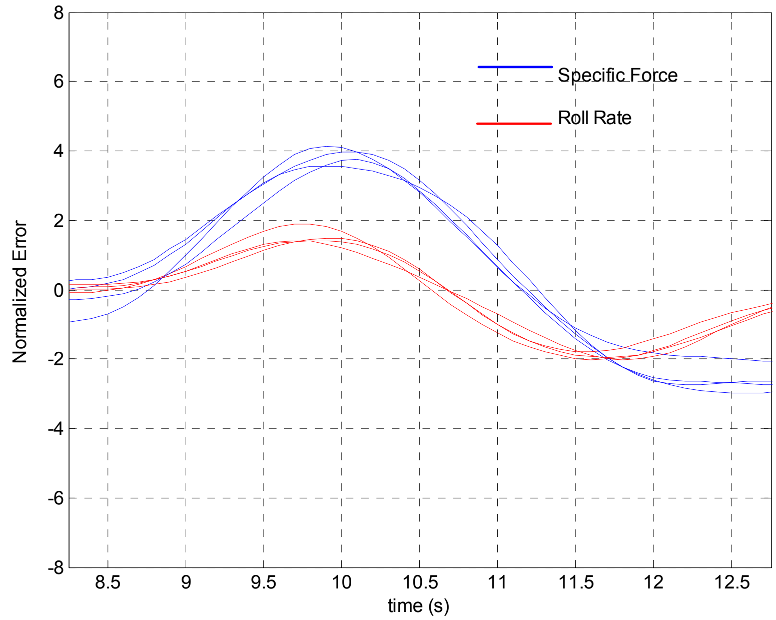

Figure 9 Normalized Errors for Subject 8, Condition CA, Right Hand Turns

The actual average normalized errors for subject 8 for both left and right turns are given in Table 2. The normalized errors are very similar to the idealized driver normalized errors given in Table 1. It is assumed similar results hold for the other subjects.

	CA Classical wxmin	CB Classical Real Nom	CC Classical Real wxmin	CD Classical Real fymin	PA LanePos Nom.	PB LanePos Low gain
$\hat{f}_y^{err}$ (m/s^2)	4	5	7	2.5	0	0
$\hat{\omega}_p^{err}$ (deg/s)	2	4.5	2	6	0	0

Table 2 Measured Average Normalized Errors for Subject 8

Paired Comparison Analysis

The following analysis of the PC data is based on David [8]. As shown in Figure 10, the total scores across the twenty-three subjects for the six different cases (CA, CB, CC, CD, PA, and PB) are 141, 109, 90, 112, 156, and 82 respectively. The score for a condition is the number of times that condition was selected over all other conditions. Thus, conditions with larger scores imply relatively more realistic vehicle motion.

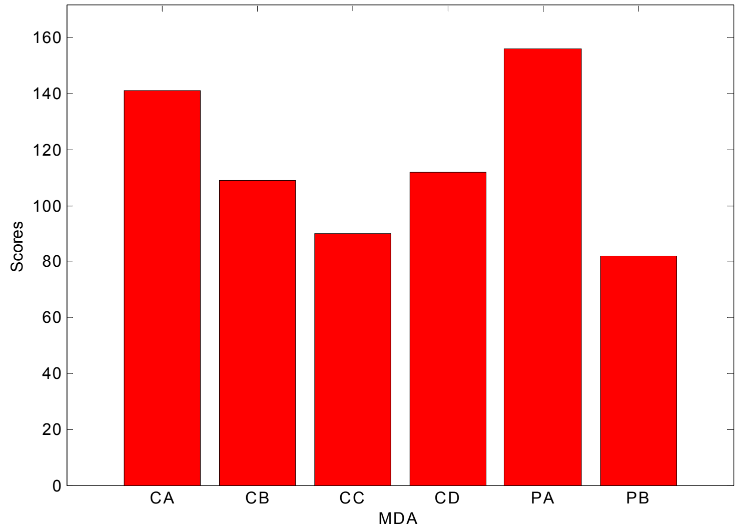

Figure 10 Total Scores

A score difference of 20 is significant at the 5% level. The MDA cases therefore divide into 3 significantly different groups, [PA, CA], [CD, CB] and [CC, PB] (In actual fact CB is not quite significantly different from CC as the score difference is only 19). The subject repeatabilities are shown in Figure 11. The repeatabilities are just the percentage of

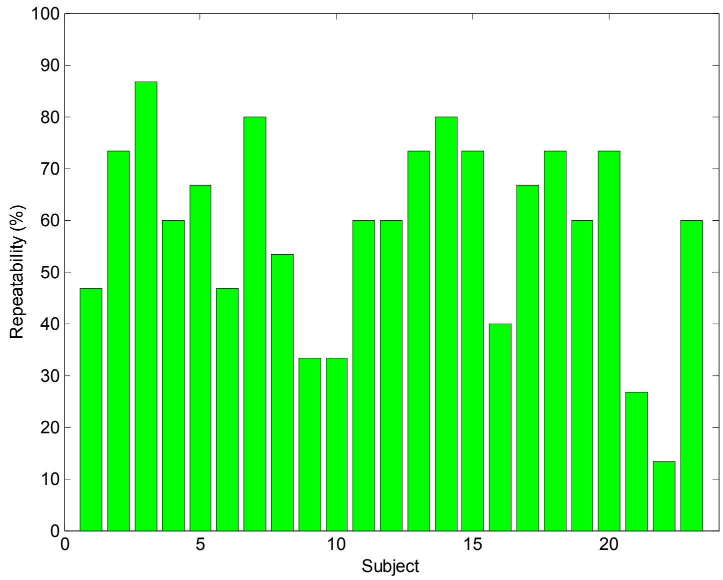

Figure 11 Subject Repeatability

time that the subjects chose the same condition in the repeated (but reversed) pairs. As can be seen the repeatabilities are quite low with an overall average of 58%. This is not surprising since half the comparisons were between tuning conditions that were not significantly different. Another measure of how well the subjects differentiated the different cases is consistency. This is a measure of the transitivity of the preferred pairs. If A is preferred to B and B is preferred to C then A should be preferred to C for consistency. The consistency is a normalized measure of consistent triads, where 100 indicates no inconsistent triads exist, and 0 indicates a maximum number of inconsistent triads exist. The subject consistency is shown in Figure 12.

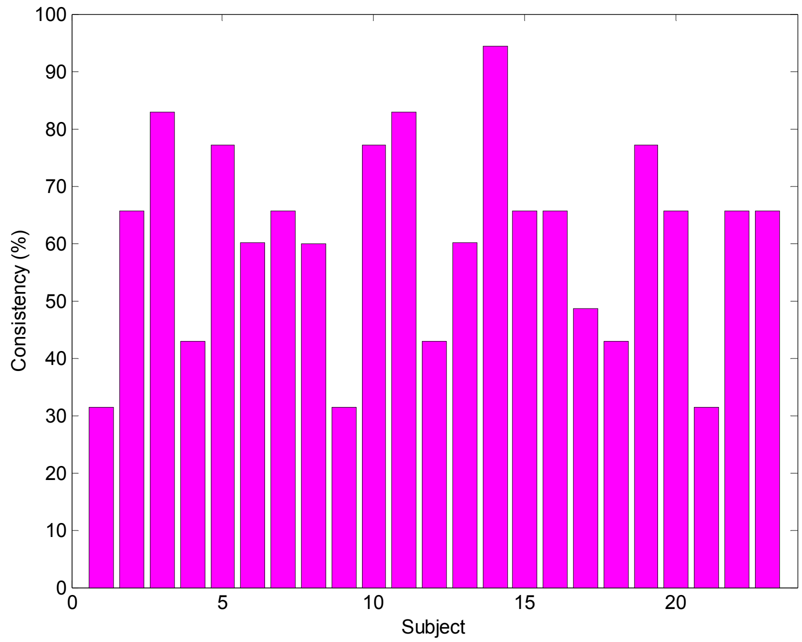

Figure 12 Subject Consistency

As with the repeatabilities, the consistency is also quite low with an overall consistency of 61%. The low result is likely due to the fact half of the comparisons were statistically insignificant. All of the data suggests that many of the various cases were difficult to distinguish.

The Bradley-Terry model [8] was fitted to the data and the Merit values are shown in Figure 13, where a higher merit value indicates the motion felt more like a real vehicle. Merit values transform the ordinal score data to an interval scale (linear scale with arbitrary zero point). The R^2 of the fit is 0.85 thus the model fits the data reasonably well. From the scores and the merit values, the order of most realistic vehicle motion is PA, CA, CD, CB, CC, and PB.

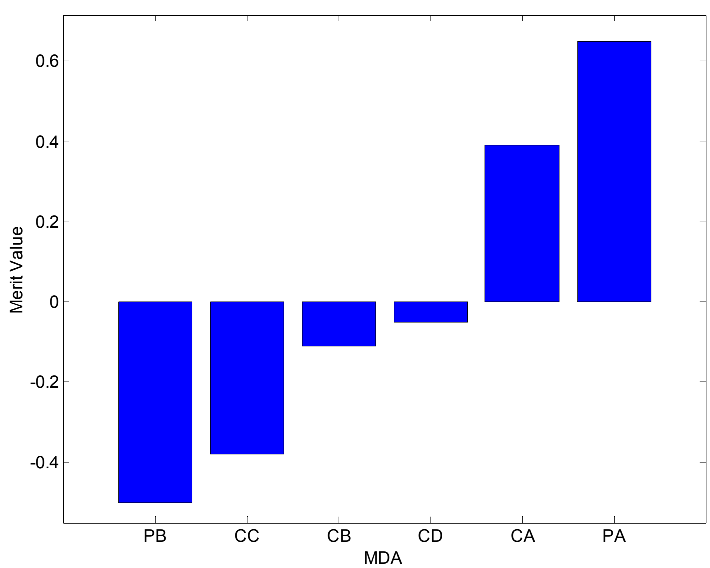

Figure 13 Merit Value

CONCLUSIONS

It was found that a maneuver specific, well-tuned classical MDA can achieve a fidelity level that approaches that of the lane position MDA. It should be noted however, that the maneuver specific classical parameter set would not be suitable for more general purpose driving. It has been specifically tuned for the given maneuver and would generate motions well beyond the capability of the VIRTTEX simulator for more severe maneuvers or for different timing between consecutive lane changes. The lane position MDA has the advantage of scaling up to more severe maneuvers (higher lateral accelerations) and being indifferent to the timing of the lane changes. More general-purpose classical MDA parameter sets do not achieve the same fidelity as the identically scaled lane position MDA. The best general purpose classical MDA parameter sets with a scaling of 0.5 were preferred to a lane position MDA with a scaling of 0.3. This suggests that the shape errors of these cases are smaller than the additional scaling error associated with a scaling of 0.3. This suggests that for a hexapod motion system a general purpose well-tuned classical algorithm is the best compromise for maneuvers which require significant combined lateral and longitudinal specific force. No strong effect in the trade-off between normalized specific force error and normalized angular rate error was found. It may be that the total error vector, rather than how it is distributed between degrees-of-freedom, is the most important factor effecting fidelity. Perhaps more likely, is that some subjects prefer one type of trade-off while others prefer another. It may also be that the length of time between trials and the extraneous motion between trials reduced the sensitivity of the method to the point where differences could not be reliably detected. Further analysis of the current data and further studies should address this question.

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