

All-Terrain Vehicle (ATV) Handling and Control, Analysis of Objective Data

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ABSTRACT

Because the great majority of All-Terrain Vehicles (ATVs) use a solid rear axle for improved off-road mobility, these vehicles typically transition from understeer to oversteer with increased cornering severity in tests customarily used by automobile manufacturers to measure steady-state vehicle handling properties. An oversteer handling response is contrary to the accepted norm for on-road passenger vehicles and, for this reason, has drawn scrutiny from numerous researchers. In this paper, an evaluation of ATV handling is presented in which 10 participants operated an ATV that was configured to have two different steady-state cornering characteristics. One configuration produced an approximately linear understeer response (labeled US) and the other configuration transitioned from understeer to oversteer (labeled US-OS) with increasing lateral acceleration in constant-radius turn tests conducted on a skid pad. After operating the ATV on a closed dirt track the participants were questioned about the handling qualities of each configuration. Participants found that the ATV with either the US or US-OS steady-state handling characteristic would be satisfactory for their typical use of an ATV; however, participants overwhelmingly preferred the US-OS Configuration. No participant reported that either configuration was unpredictable, although the US-OS configured ATV was rated as more comfortable and received better steering feedback ratings for tight turns compared to the US Configuration. A detailed discussion of the participant responses is provided in [1] while the objective steering and vehicle response data and video collected in the study is the focus of this paper. Consistent with the participant's feedback, the objective data did not indicate that there was a control issue associated with the ATV configured to have an understeer/oversteer steady-state handling response.

CITATION: Fowler, G. and Larson, R., "All-Terrain Vehicle (ATV) Handling and Control, Analysis of Objective Data," *SAE Int. J. Veh. Dyn., Stab., and NVH* 1(2):2017, doi:10.4271/2017-01-1557.

INTRODUCTION

Since 1985 the U.S. Consumer Products Safety Commission (CPSC) has conducted or sponsored numerous studies related to the use and the design of ATVs including investigations into their handling characteristics. Because ATVs use a solid rear axle or a direct gear drive to both rear axles for improved off-road traction, these vehicles typically transition from understeer to oversteer with increased cornering severity. An oversteer handling response is contrary to the accepted norm for on-road passenger vehicle handling due to the potential for directional instability at higher speeds which could increase the risk of loss of control. For this reason, ATV's handling characteristics have drawn scrutiny from the CPSC staff and other researchers. In some early research sponsored by the CPSC, for example Allen [2], the ATVs' handling characteristics were investigated both analytically and using traditional automotive handling tests. The authors reported that the ATV's oversteering characteristic could result in dynamic instability and potential spin out under hard cornering. They did note, however, that their study did not establish how often, or under what circumstances, riders encounter these limit performance conditions. Recently, the CPSC has renewed its effort to investigate the handling characteristics of

ATVs and contracted SEA Limited to conduct handling tests and stability evaluations of a selection of recent model year ATVs [3]. At this time, however, the mandatory ANSI/SVIA standard for four wheel ATVs does not include a handling requirement [4].

In other early investigations, Fowler [5] confirmed the tendency for ATVs to transition from understeer to oversteer at relatively low lateral accelerations, although the authors concluded that operation in the oversteer regime could still be achieved without undue demand on the operator to maintain directional and roll stability. Forouhar [6] used a classical control theory approach by experimentally identifying the transfer function of an ATV's lateral directional dynamics and then used the "crossover" model for the ATV/rider system to study the role and effectiveness of the rider in achieving and maintaining directional control. This approach had been previously applied to examine control aspects of aircraft and passenger cars. The author concluded that an ATV with limit oversteer can be effectively stabilized by the rider's compensatory feedback through body movement and throttle control.

More recently, Renfroe [7] examined the directional response of some stock ATVs concluding that ATVs had handling characteristics that “traditionally have been found to not be conducive to vehicle control or safety.” By “traditionally” it is presumed the authors are referencing the control of passenger vehicles which, in steady state circle turn tests, maintain an understeer response to the limit. The authors present the thesis that by adjusting the handling characteristics of ATVs to more closely mirror that of on-road automobiles, the driver demand is reduced and driver confidence in maneuvering the vehicle is increased. The implication is that such modifications would improve the safety of ATVs citing “a possible connection between control and crash frequency.”

As part of this study the handling characteristics for some stock and modified ATVs were reported based upon circle turn tests on a paved surface. The stock ATVs tested initially understeered at low lateral accelerations and transitioned to oversteer with increased speed on the circle. A modified ATV, with an independent rear suspension and a lockable differential such that, when the differential is unlocked it functions like a typical passenger car allowing the rear wheels to rotate at different speeds, exhibited a more neutral to slight understeering response in the circle turn tests. The stock and modified ATVs were operated on an oval gravel course at speeds that appear to be approaching the cornering limits of the vehicle/rider systems. The data showed the rider inputting larger oscillatory steering corrections when operating the stock ATV compared to the modified ATV with the rear axle unlocked. The authors pointed to the steering oscillations as evidence of the stock ATV’s unpredictable handling and the rider reportedly noting much more confidence operating the modified ATV.

With the stated intention of addressing serious injuries and fatalities associated with workplace-related off-road vehicle-related incidents in Australia, an Australian Terrain Vehicle Assessment Program (ATVAP) consumer safety star rating system has been proposed which includes a series of tests intended to assess the static stability, dynamic handling and rollover crashworthiness of ATVs and side-by-sides or UTVs [8, 9]. One element of the proposed star rating system is a steady-state 7.6 m (25 ft) circle turn test conducted on a paved surface that “scores” the vehicle’s understeer or oversteer characteristic and the point of transition between understeer and oversteer. Other elements included in the dynamic handling overall score are the lateral acceleration at which two-wheel lift or slide-out occurs, steering response time, bump obstacle perturbation and, whether the vehicle has a lockable differential.

As summarized in [8] the developers of the proposed star rating assert that, “In order to provide predictable and forgiving handling characteristics while remaining responsive and highly mobile, ... a vehicle should be designed to provide a light understeer response of between 1 to 2 degrees per g lateral acceleration” in a steady-state 7.6 m (25 ft) radius circle turn test on pavement. Furthermore, this understeer characteristic should continue to at least 0.5g lateral acceleration. Vehicles that demonstrated this characteristic will receive a higher rating Index value.

In the supporting documentation for the dynamic handling star rating, the developers do not provide evidence that the handling characteristics rated most highly will positively impact accident risk. In [9] they draw upon past analyses of automobile control and the CPSC’s analysis of the Yamaha Rhino’s reported incident data [10]. However, an important distinction directly related to handling and control between ATVs and passenger cars, as well as side-by-side (SxS) vehicles, is that ATVs are rider-active, handlebar steering vehicles with a minimal steering reduction. For example, 10 degrees of ATV handlebar angle translates to a similar degree of front wheel steer angle whereas, for a typical passenger car, 10 degrees of wheel angle would require around 180 degrees of steering wheel angle. This represents a very different control model for the two vehicles since steering corrections can be accomplished much more directly and quickly on an ATV than in a passenger car. In this respect the rider is in more direct communication with the operational state of the vehicle. Consequently, drawing upon the experience of steering wheel controlled and physically larger vehicles may not be directly applicable to ATVs.

Furthermore, operating a vehicle with an oversteer limit handling characteristic does not necessarily imply that it is difficult to control or the vehicle is directionally unstable when operating in that regime. Up to a point, steering control remains, so that operators can maintain a desired path through steering and throttle control. The increased steering activity when operating in the oversteer regime, the feeling that the rear tires are breaking loose and, the increasing response times provides very recognizable feedback to the operator that the cornering limit is approaching.

In this paper, an evaluation of ATV handling is presented in which participants, recruited for the study, operated an ATV that could be configured to have two different steady-state cornering characteristics as documented in circle-turn tests on an asphalt surface. One configuration produced an approximately linear understeer response (labeled US) while the other configuration transitioned from understeer to oversteer with increasing lateral acceleration or speed on the circle (labeled US-OS). Ten riders operated the ATV in both configurations on a serpentine off-road riding course and were asked to complete a questionnaire to gather subjective impressions regarding the vehicle’s handling response, controllability and suitability of purpose. All the subjects riding were videotaped and the ATV was also instrumented to record objective performance and rider input data. A detailed discussion of the participant’s subjective feedback is provided in [1] and is only briefly summarized here. This paper presents an analysis of the objective steering and vehicle response data and video collected in the study. The participant’s questionnaire responses are also discussed in light of the objective data.

TEST DESIGN

Vehicle Selection

The ATV used in the study was a mid-sized general purpose/utility model with a 420 cc engine (Figure 1). The ATV came equipped with front and rear independent suspension, a selectable 4th gear, a manual transmission and, two- and four-wheel-drive capability. An

ATV with these general specifications was chosen because its size would be suitable for all adults, the participants in the study would not need to change gears during their evaluations and the suspension could be modified relatively easily to obtain the different steady-state cornering characteristics. The ATV was instrumented to record yaw, pitch and roll angles and associated angular velocities, the three principal linear accelerations, speed and GPS position. An OXTS RT-3003 precision Inertial and GPS Navigation system was used to generate the vehicle kinematic and positional data. A GPS base station was utilized to optimize the accuracy of the positional data. In addition, the operator's control inputs, including handlebar angle, throttle and brake application were also recorded. A Space Age Control 162-3405 string potentiometer was used to measure steering angle, throttle input was obtained by monitoring the vehicle's throttle position sensor, and brake event was monitored by recording the brake light voltage. The RT 3003, signal conditioning and data acquisition equipment were housed in a Pelican case on the rear rack, and the GPS antennas were mounted on the front rack.

Video was recorded throughout each test run with a panning high-definition camera on an aerial lift, and in select turns with a ground based panning camera. A flash was installed on the vehicle to allow for synchronization of the recorded data and video.



Figure 1. Test ATV with instrumentation.

Steady-State Handling Response

To create the two steady-state cornering responses used in the study, the front and rear suspensions were modified with the installation of an additional front and rear sway bar which were independently connected or disconnected. The steady-state response for each suspension setup was characterized using a constant radius turn test circle turn procedure on a 7.6 m (25 ft) radius asphalt surface¹. The test procedure involved starting from rest and slowly increasing speed while adjusting the handlebar angle to keep the ATV centered on the circle until a steady-state trim condition could not be maintained or the operator perceived the vehicle approaching the stability limit. Both left and right turn directions were run and an example plot of the front wheel angle as a function of lateral acceleration for the right turn is shown in Figure 2.

1. The circle radius and surface was chosen so as to match the procedure outlined in the TARS report [8].

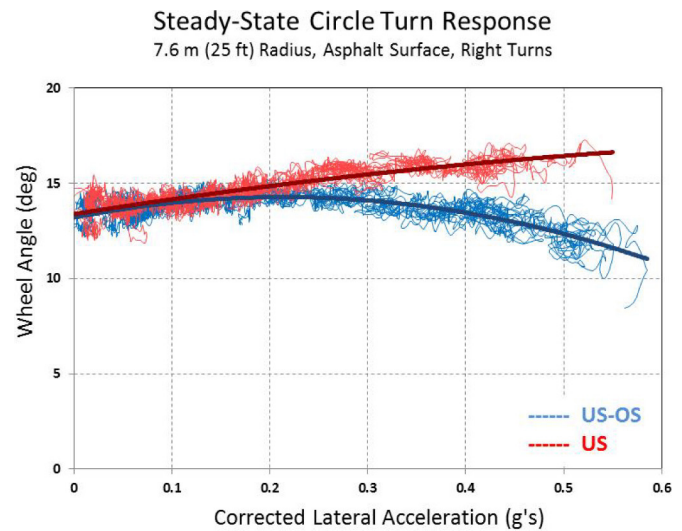


Figure 2. Steady-state steering characteristics for US-OS and US configurations (right turn).

The ATV with the front sway bar attached (labeled US) yielded an approximately linear understeer steering response. Disconnecting the front sway bar and adding an additional rear sway bar produced a steer wheel angle versus lateral acceleration response that transitioned from initially understeer (positive slope) to oversteer (negative slope) and was labeled US-OS. The understeer gradients for the two configurations measured at 0.1 g and 0.4 g are provided in Table 1 and are based on fitting a second-order polynomial to the wheel angle data in Figure 2. For the US-OS Configuration the neutral steer points were approximately 0.21 and 0.15 g's in the right and left turns, respectively.

It should be noted that the modifications to the ATV's suspension were intended to provide a mechanism to investigate the influence of different steady-state cornering characteristics on riders' subjective impressions of an ATV's handling when operating on the off-road course. Numerous other factors, such as off-road mobility, bump and vibration absorption, and the range of expected uses would also be considered when optimizing an ATV's suspension design – these are not considered in this study.

Table 1. Understeer gradients measured at 0.1 and 0.4 g's.

Lateral Acceleration (g's)	Understeer Gradient (degrees/g) Right turn (R), Left turn (L)	
	US Configuration	US-OS Configuration
0.1	7.3 (R) 5.3 (L)	5.3 (R) 2.0 (L)
0.4	4.9 (R) 3.1 (L)	-8.8 (R) -9.7 (L)

Test Course

A 975 m (3,200 ft) riding course at Exponent's Test and Engineering Center in Phoenix, Arizona was used to evaluate the handling characteristics of the two ATV configurations (Figure 3). The course was designed to incorporate the types of turns that might be performed during ATV utility and general transportation appropriate for the class of general purpose ATVs used in the study. The turn radii

ranged from 18 m (60 ft) with a decreasing radius in turn 18 to tight turns requiring full steering lock (turns 12 and 28). The test surface consisted primarily of hard packed desert dirt with some sections of coarse sand and gravel (Figure 4). The surface was watered for dust control which made some areas a little muddy and more slippery at times. The course was periodically groomed to help mitigate the formation of ruts. The nature of the surface conditions on the test course resulted in a relatively low friction surface and, therefore, tended to place a high premium on directional control. The course was intentionally made on predominantly level ground, focusing on lateral dynamics rather than pitch behavior.

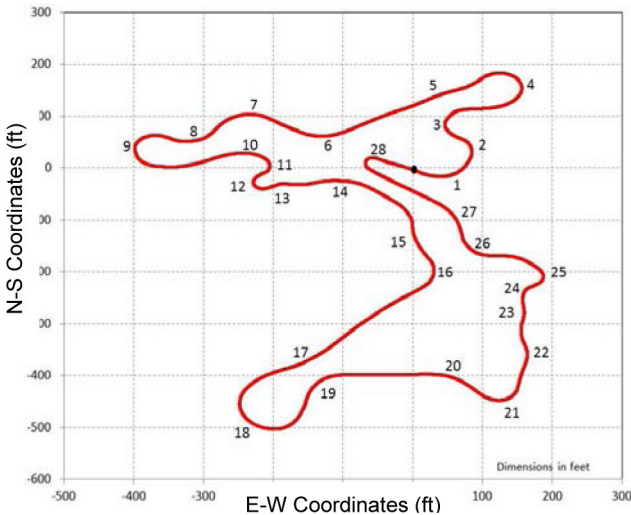


Figure 3. Course layout with turn numbers indicated.



Figure 4. Test course surface and representative turns. Turns 2 and 3 (upper) and Turn 12 (lower).

Participants and Instructions

Participants that were over 25 years of age and had more than one year of ATV riding experience were recruited for the study so that they were not learning or uncomfortable operating an ATV on the test course during the evaluation. Ten participants (eight male and two female) ranging in age from 31 to 67 years were included in the study. The participants' weights ranged from 68 to 127 kg (150 to 280 lbs). All but one participant reported 15 to 30 years of experience operating ATVs with 0 to 150 hours of riding within the last year. The oldest participant was retired and reported the most riding time in the last year. The least experienced participant reported 3 hours of riding time in the last year. Eight of the 10 riders rode sport/recreation ATVs while the remaining two operated general purpose/utility ATVs. In the participant questionnaire, participants were asked to circle which words best described their ATV usage. The results revealed that all but one participant used their ATV for trail riding while the next most popular descriptive words indicated occasional use, sightseeing and operation at moderate speed. The responses to this question were not unexpected given all the participants except one (who sometimes used his ATV for utility purposes) were from the Phoenix area. All but one rider had experience with other off-road vehicles. None of the riders reported taking an ATV training course.

The participants were initially briefed that the purpose of the study was to obtain feedback regarding the handling of an ATV with two different suspension set-ups labeled "A" and "B". To accomplish this, they were to operate the ATV with each setup for three laps on a course marked with cones. The first lap was at a lower speed, so that they could get familiar with how the ATV handled, and only the second and third laps were utilized for the analysis. Participants were instructed to briefly pause in between in each lap so the instrumentation could be zeroed prior to the next lap. After the third time through the course, they were asked to fill out a short questionnaire about their experience operating the ATV. After filling out this survey, subjects were informed that several aspects of the ATV had changed and were asked to operate the ATV in a similar fashion as their initial set of laps, but told to evaluate the ATV on the second set of laps independently from their first set. The participants were also instructed to operate the ATV in a safe manner that they felt comfortable with and consistent with their skill level. It was reiterated that this was not a competition. On the first of the three laps with each configuration, they were instructed to proceed at a slow pace so as to get some familiarity with how the ATV with that set-up handled. Further, instructions included that they try and keep within the coned course but, if they found that they could not stay within the boundaries of the course, they were not to overreact and try an unsafe maneuver in an attempt to regain the course. Participants were told that, if that happened, to just exit the course (they could run over the cones), slow down and safely reenter and continue. If, at any time, they felt uncomfortable completing the study, participants were instructed to just stop the ATV and let one of the observers know they did not wish to proceed and they would still be reimbursed for their participation.

Before beginning the first of the two sets of three laps on the ATV, participants were asked to mount the ATV and were shown the controls. The ATV transmission was set to the automatic mode so no

gear shifting was required. The participants could then, if they desired, operate the ATV at a slow speed on level open terrain to become familiar with the throttle response and brakes. To initially familiarize the participants with the course, they were then instructed to follow another ATV around the course at a slow speed. At the completion of this lap the participants were instructed to begin their first set of three laps. The configuration order was counter-balanced between the participants. After operating both configurations and completing the questionnaires, participants were asked which configuration they preferred.

DISCUSSION OF RESULTS

Summary of Participant's Subjective Responses

A detailed analysis of the participant's responses to the survey questions completed after the operation of the ATV in both configurations is provided in [1]. A summary of the findings include:

- Participants in the study found that the ATV with either the US or US-OS steady-state handling characteristic would be satisfactory for what they used an ATV for, but participants overwhelmingly preferred the US-OS Configuration. This included those participants reporting a range of riding styles, the oldest participant, the least experienced participant, and whether the participants personally operated general purpose/utility or sports/performance ATVs.
- No participant indicated that either configuration responded unpredictably to their steering inputs.
- No significant difference was found between the configurations when participants rated their subjective effort to stay on the course.
- Participants reported significantly higher comfort operating the US-OS Configuration than the US Configuration.
- The terms used by participants to evaluate the ATV's steering were generally more positive when evaluating the US-OS Configuration than the US Configuration.
- Steering feedback was rated significantly higher for the US-OS Configuration in tight, slow turns.
- The majority of ATV operators experienced the rear of the ATV sliding and the vast majority of those participants indicated that action was purposeful.
- The US-OS configured ATV was not difficult to control according to the participants.

Data and Video Analysis

The video and recorded data were analyzed to provide insight into whether differences existed in the participants' control inputs and the response of the two ATV configurations, and to investigate relationships between the participant's subjective observations and the objective data².

The average speed during laps 2 and 3 for each participant while operating both configurations is provided in [Appendix A](#). The participants' subjective rating of their comfort level is also provided and shows how the participants tended to rate the US-OS Configuration as the same or more comfortable than the US Configuration, even when operating the vehicle at higher average speeds.

Lateral Acceleration Affordances

The participants' reported riding style on the course ranged from "aggressive" and "pushing the limits" to "moderate" and "slow" which would suggest differences in straight line and cornering speeds on the course would be observed in the data. In [Figure 5](#) and [Figure 6](#) the corrected lateral acceleration recorded for all three laps is plotted against speed for Participants 4 and 6³. Participant 4 recorded the shortest lap times amongst all the participants in both configurations during lap 3 with average speeds of 28 kph when operating both the US-OS and US ATVs. He noted that he was operating at a "high speed" and "pushing the limits." Participant 6, according to the questionnaire response, varied his riding style between the two configurations noting that, when operating the US-OS Configuration he rode at a "slow speed" in lap 2 (average 23 kph) and "moderate" speed in lap 3 (24 kph). In contrast when riding the US Configuration he reported that he went at a "moderate" speed in lap 2 (24 kph) and "high speed" in lap 3 (26 kph). For these participants the differences in the reported riding styles was reflected in the data with Participant 4 cornering at consistently higher lateral acceleration levels (around 0.5 g's with occasional peaks to 0.6 g's) and maintained at higher speeds (30-35 kph) than that observed for Participant 6 (typically 0.4 g's with no peaks reaching 0.6 g's). Another difference between these participants was the speed at which each rider began to reduce their maximum lateral acceleration levels. In both configurations, Participant 6 reduced the higher cornering accelerations at approximately 8 kph lower speed than Participant 4. Participant 6's reported change in riding style between the two configurations was also reflected in the data plots indicating his subjective interpretation of his performance matched the objective data.

The combination of Participant 4's description of his riding style and the corrected lateral acceleration data indicates that the maximum cornering capacity of the ATV due to tire friction limitations on the course was approximately 0.5 g's. Higher transients were short duration and likely associated with non-level surfaces, changes in surface friction and ruts and steering transients. Participant 4, and others, were comfortable operating at the tire traction limits based upon their responses to the questionnaires and the recorded lateral accelerations. Both the US-OS and US Configurations offered sufficient control for these participants who chose to operate at that level.

2. For Participants 1 and 2, the GPS data channels were corrupted. As a consequence, speed and position data was not analyzed for these riders.

3. The acceleration data was filtered at 2 Hz (as higher frequencies are unlikely to influence the response of the ATV/rider system) and are corrected to horizontal plane. The surface of the course was not consistently level and did contain low frequency changes, cambers and ruts so the lateral acceleration may not reflect the cornering forces acting parallel to the surface at all points on the course.