Driveability issues of the Zero-Inertia powertrain

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Summary

This report focuses on assessing the driveability for the Zero-Inertia vehicle, part of the Ecodrive project at Eindhoven University of Technology, in association with Van Doorne's Transmissie (VDT) and Netherlands Organization for Applied Scientific Research (TNO).

Driveability is defined in this report as:
"The driver-vehicle-environment interaction with respect to the performance of the vehicle's powertrain."

Driveability is usually rated subjectively by test drivers, but attempts are being made to assess it objectively with correlation analyses by means of linear regression or neural networks.

Several phenomena have been addressed, and it was found that there are a couple of scales on which to rate driveability (phenomena).

An important issue for CVT vehicles is the delay time, followed by a sudden kick-down action.

The ZI-vehicle, with its additional flywheel, coupled by a planetary gearset, can solve this problem in theory.

Driveability analysis for low speeds (starting speeds of 0 and 12 km/h) for the ZI in simulation shows the driveability rating predicted is above 8 for 0 km/h and 7.3 for 12 km/h on a scale from 1 to 10.

At starting speeds from 30, 50 and 80 km/h, the ZI outperforms the CVT at all speeds, especially at reducing the dead time from 0.5 s to 0.1 s, and eliminating inverse responses.

At 50 km/h the ZI reduces the discomfort compared to its original 4-speed automatic gearbox with over 20 %, at 80 km/h the ZI even performs more than 50 % better.

When the ZI-equipped car is ready for testing including its flywheel, a final driveability rating can be determined, including test drivers' judgements.

Suggestions for these assessments have been given.
## Nomenclature

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Unit(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \frac{d}{dt} )</td>
<td>CVT ratio change rate</td>
<td>[ \frac{1}{s} ]</td>
</tr>
<tr>
<td>( t )</td>
<td>Time</td>
<td>([s])</td>
</tr>
<tr>
<td>( t_0 )</td>
<td>Time of observation</td>
<td>([s])</td>
</tr>
<tr>
<td>( \tau )</td>
<td>Integration time for running averaging</td>
<td>([s])</td>
</tr>
<tr>
<td>( a_{rms} )</td>
<td>R.m.s acceleration</td>
<td>[ \frac{m}{s^2} ]</td>
</tr>
<tr>
<td>( a_{rrms} )</td>
<td>Running r.m.s acceleration</td>
<td>[ \frac{m}{s^2} ]</td>
</tr>
<tr>
<td>( a_{W(t)} )</td>
<td>Weighted acceleration</td>
<td>[ \frac{m}{s^2} ]</td>
</tr>
<tr>
<td>( T )</td>
<td>Time window</td>
<td>([s])</td>
</tr>
<tr>
<td>( VDV )</td>
<td>Fourth power vibration dose</td>
<td>[ \frac{m}{s^2} ]</td>
</tr>
<tr>
<td>( MTVV )</td>
<td>Maximum transient vibration dose value</td>
<td>[ \frac{m}{s^2} ]</td>
</tr>
<tr>
<td>( W_d )</td>
<td>Fore-aft acceleration weighting filter (seat-surface)</td>
<td>([-])</td>
</tr>
<tr>
<td>( W_c )</td>
<td>Fore-aft acceleration weighting filter (seat-back)</td>
<td>([-])</td>
</tr>
</tbody>
</table>
1. Introduction

This report puts focus on assessing the driveability for the Zero-Inertia Vehicle, part of the Ecodrive project at Eindhoven University of Technology, in association with Van Doorne's Transmissie (VDT) and Netherlands Organization for Applied Scientific Research (TNO).

Firstly the term driveability will be explained and general driveability phenomena and ways to assess vehicle driveability will be dealt with.

Secondly several general driveability issues are addressed, after which the driveability with respect to vehicles equipped with Continuously Variable Transmissions is treated.

Thirdly the differences between driveability of CVT and non-CVT equipped vehicles will be compared.

After a brief explanation of the torque-assisting Zero-Inertia (ZI) powertrain, its driveability will be investigated at low speeds and at higher speeds.

The Zero-Inertia powertrain will be introduced, and its operation explained.

Then the ZI driveability at low speeds will be investigated, followed by the ZI driveability at higher speeds.

Complementing this, the ride comfort of the ZI will be assessed.

Finally, conclusions and suggestions for further investigation will be given.
2. Driveability in general

2.1 Definitions

What is driveability? What is handling?

The definition of handling [1]:
"An interaction between driver, vehicle and environment, which takes place during transportation of people or goods from place to place".

This quite a general definition. So a subjective assessment of handling also comprises a vehicle's drivetrain. It is interesting to remark that most publications concerned with handling do not address the drivetrain of a vehicle, but focus more on a vehicle's directional response properties.

A driver's subjective assessment of drivetrains is usually described by driveability. So this may be considered as a part of the total envelope of vehicle handling properties. Let's illustrate this by stating a few definitions/discriptions of the term driveability:

"Driveability describes how dependably and smoothly a car's power train operates under all kinds of weather and operating conditions. Driveability does not include ride and handling quality, braking performance, or abnormal combustion phenomena such as knock." [2]

"Good vehicle driveability is characterised by the driver having ease of control of the vehicle and confidence in both predictable and desirable system responses to the driver's demands. It is very much dominated by the performance of the powertrain and vehicle in transient conditions." [3]

The first definition considers the handling of a vehicle as a separate issue. Also abnormal combustion phenomena are excluded, however a vehicle with combustion problems can be said to have a disappointing driveability.

The second statement (description) describes driveability as a driver-vehicle interaction, with respect to powertrain and vehicle.

Let us formulate a new definition of driveability:
"The driver-vehicle-environment interaction with respect to the performance of the vehicle's powertrain."
2.2 Why focus on driveability?

A lot of attention in the automotive industry has been given to the reduction of fuel consumption and abatement of emissions. When making improvements in these fields, driveability must always be taken into consideration, and a compromise is imperative.

Fuel consumption and emissions can be measured and rated objectively. However, until recently, driveability has only been rated subjectively through test drivers carrying out driving test manoeuvres on a prototype or production vehicle and filling out evaluation forms.

This is costly and time-consuming work, with still subjective ratings and limited repeatability. [4]

Handling and thus driveability is often a decisive factor for a customer when he/she subjectively assesses the car during a road test.

It is therefore important that reliable and objective driveability information is available from the early stages in the design process of an automobile or parts of the drivetrain.

That is the reason why more and more effort is invested in finding ways to rate driveability in an objective manner and earlier on in the design process, e.g. by computer and hardware-in-the-loop simulations.

2.3 Malfunctions

Some terms to describe driveability (malfunctions) are now explained [2],[5]:

Start time
The cumulative time needed to start the engine and have it run idle for a prescribed time.

Stall
The engine cutting out with the ignition on. This can happen during idling, acceleration and deceleration.

Idle quality
Smoothness of the engine during idling (running of the engine with the gearbox in neutral).

Hesitation
A temporary lack of initial response in acceleration rate (time delay).

\[
\begin{align*}
\text{Acceleration} \\
\text{Time}
\end{align*}
\]

Figure 2.1: Hesitation

Sag or stumble
A short, sharp reduction in acceleration rate, a loss of power.
Sag is less severe than stumble, the latter shortly showing a deceleration.
Backfire
An explosion in the intake or exhaust system.

Surge
A continued condition of short, sharp fluctuations in power, often caused by cyclic power variations in the engine, more pronounced when using lean air-fuel mixtures.

Shuffle
Fore- and aft longitudinal oscillations in vehicle acceleration [6], generally caused by powertrain oscillations during transient manoeuvres.

Stretchiness
Lack of acceleration performance during light to moderate accelerations.

After-run
Running of the engine after ignition cut-out.

Vapor lock
Loss of acceleration, stalls, failure to start due to excessive gasoline vapor in critical parts of the fuel system.

Carburetor icing
Performance loss due to ice formation in the intake system.
2.4 Test manoeuvres to evaluate driveability

Below a number of driving manoeuvres [2] to evaluate driveability during a test drive are addressed. This list is not exhaustive nor complete, but merely to give an impression of what kind of tests are possible.

Driving manoeuvres

- **Starting**
  Starting the vehicle, cold or hot (soaked)

- **Idle**
  Running of the engine in neutral at zero speed

- **Detent acceleration**
  Opening the throttle without causing a downshift by the automatic transmission

- **Wide Open Throttle (WOT) acceleration**
  An acceleration made entirely at wide open throttle

- **(constant) Part Throttle (PT) acceleration**
  An acceleration made at any fixed throttle position less that WOT

- **Crowd acceleration**
  An acceleration maintaining a fixed vacuum in the inlet manifold

- **Tip-in**
  A manuever to evaluate vehicle response (up to 2 sec in duration) to the initial opening of the throttle

- **False starts**
  Opening and immediate closing of the throttle

- **Cruise**
  Driving at constant speed

- **Deceleration**
  Coast-down/sudden stops

- **Back out**
  Release of the drive pedal during cruise/acceleration

- **Gear shift**
  Shifting up/down

Often anchoring is used, sometimes even without the test driver's knowledge. Anchoring is to let the test driver find (high and/or low) reference points. For example during surge measurements the car is allowed to coast down with the gearbox in neutral [2] so that engine-caused vibrations cannot be felt, or by making a vehicle with exceptional shift quality worse [7].

2.5 Driveability rating

The subjective responses of test drivers are usually assessed by letting them fill out questionnaires after the tests and by gathering the driver's feedback during the tests.

Some researchers subjectively rate the malfunctions individually, using a 4-ratings severity scale:
Table 2.1: 4 ratings severity scale

Start time (in seconds) and stall (# of occurrences) can be rated objectively. To obtain a rating for total driveability, the total weighted demerits (TWD) are calculated, by summing the ratings with scaling factors for severity and phenomena [5].

Surge rating in the method developed by the Coordinating Research Council (CRC) is done using the following 5-ratings scale [8]:

<table>
<thead>
<tr>
<th>None</th>
<th>Nobody can notice</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trace</td>
<td>Technically trained driver can notice</td>
</tr>
<tr>
<td>Light</td>
<td>Average driver can notice</td>
</tr>
<tr>
<td>Moderate</td>
<td>Average driver feels uncomfortable</td>
</tr>
<tr>
<td>Heavy</td>
<td>Average driver feels very uncomfortable</td>
</tr>
</tbody>
</table>

Table 2.2: 5 ratings severity scale

Total driveability can also be rated on a scale from 1 to 10, 1 being the worst driveability and 10 the best [7],[10]. [4] describes these as in Table 2.3 below.

<table>
<thead>
<tr>
<th>10</th>
<th>Not noticeable even by experienced test drivers</th>
</tr>
</thead>
<tbody>
<tr>
<td>9</td>
<td>Disturbing for experienced test drivers</td>
</tr>
<tr>
<td>8</td>
<td>Disturbing for critical customers</td>
</tr>
<tr>
<td>7</td>
<td>Disturbing for critical customers</td>
</tr>
<tr>
<td>6</td>
<td>Disturbing for all customers</td>
</tr>
<tr>
<td>5</td>
<td>Very disturbing for all customers</td>
</tr>
<tr>
<td>4</td>
<td>Felt to be deficient by all customers</td>
</tr>
<tr>
<td>3</td>
<td>Reclaimed as deficient by all customers</td>
</tr>
<tr>
<td>2</td>
<td>Limited vehicle operation only</td>
</tr>
<tr>
<td>1</td>
<td>Vehicle not operating</td>
</tr>
</tbody>
</table>

Table 2.3: 10 ratings severity scale

2.6 Correlation techniques

After determining how the car is performing, these subjective ratings can be correlated to the objective data measured during the drivability tests. If a good
correlation can be found between the objective data and the driveability ratings, this
correlation can be used to predict driveability from objective data, even reliable
simulation data can be used. The need for reference vehicles in the benchmarking
would be removed, the repeatability and spreading improved and quantitative data
would be available for use in vehicle and calibration development [11].
Of course a lot of effort is needed as a large number of test drivers and cars are
necessary to obtain accurate data.
The data to derive a driveability estimate from changes with time, as drivers’
expectations of a vehicle do. So the calibration of a vehicle’s driveability must be kept
up to date.
To correlate objective data to subjective ratings first some criteria must be selected
for which a driveability rating is required.

Criteria selection
Some examples are shift quality [7], surge [2]. Some try to rate driveability as a
whole, which of course demands a much higher number of phenomena to take into
account [4].
A list of commonly used criteria is stated below [2], [4]:

- Cold start
- Hot start
- Idle
- Engine start
- Tip in
- Let off (Back out)
- Acceleration
- Closed throttle behaviour
- Roll on stop
- Warm up behaviour
- Pedal steering control
- Gear change
- Cruise (or road load)
- Deceleration
- WOT low end torque

Parameter selection
A number of parameters are selected that describe that part of driveability to be
considered. This is a means of data-reduction by selecting certain parameters that are
believed to be correlated to the driveability criteria to be assessed, based on the
experience and expectation of the researcher.
Depending on the driveability criteria to be judged, a number of parameters is
selected, but fore and aft (longitudinal) accelerations and jerk are generally always
taken into account e.g. [7],[12].
In the research for shift quality some researchers only used the driveline torque traces,
but found that critical body resonances don’t show up in the torque traces [7]. Schwab
[7] also found that driveline lash filtered out body resonances above 5 Hz. He further
used the maximum average power of accelerations (during a shift event):
\[
\text{max. average power} = \max \left( 10 \int_{t_0}^{t} \left[ a(t) - a_{\text{mean}} \right]^2 dt \right), \quad 0 \leq t_0 \leq T
\]

Where:
- \( a(t) \) the acceleration trace \([\text{m/s}^2]\)
- \( a_{\text{mean}} \) the mean acceleration during the shift event \([\text{m/s}^2]\)
- \( t \) the time (integration variable) \([\text{s}]\)
- \( t_0 \) the time of observation \([\text{s}]\)
- \( T \) time window \([\text{s}]\)

Finally the peak-to-peak value of the 10-14 Hz contribution in the acceleration trace was used.

Everett [2] also used the average power of acceleration fluctuations, in order to measure surge:

First the signal \( a_w \) is obtained by band-limited filtering of the acceleration signal between 0 and 10 Hz.

\[
\text{average power} = \int_{t=0}^{40} [a_w(t)]^2 dt
\]

Where:
- \( a_w(t) \) the filtered acceleration signal \([\text{m/s}^2]\)
- \( t \) the time (integration variable) \([\text{s}]\)

Anderson and Bierley [13] considered vertical accelerations and pitch velocity, but they found that the fore-aft acceleration and jerk were the primary indicators of shift feel.

**Measurement selection**

Objective measurements, from which the previously selected parameters can be obtained, are gathered during a number of different driving manoeuvres, by various test drivers, and often for various car models. [7],[12].

The measurements taken during the several manoeuvres to be performed of course depend on the selected parameters, and often consist of:

- Longitudinal vehicle acceleration
- Engine and vehicle speed
- Pedal position
- Throttle position

After performing these tests, the driveability parameters are calculated.

In order to predict the driveability rating from objective measured and calculated driveability parameters, a couple of different correlation techniques are used.

Most commonly a linear regression analysis is used to obtain a relationship between the driveability parameters and the driveability rating. [7],[10].

Another method to correlate the subjective data to the objective parameters is to use a neural network. The driveability parameters are then used as inputs and the driveability rating as output [7],[4].
Simultaneously with the objective measurements, subjective judgements from the test drivers are recorded during and after the tests. In the case of [7], the driver expressed a rating between 1 and 10 at each shift event. In [14] the step-by-step instructions included in Appendix 1 clearly show how and when a driver’s malfunction judgement is taken.

[7] found that a driver’s subjective assessment became nonlinear for the peak to peak acceleration and jerk values during severe maneuvers. This supports that a correlating (linear) relation between subjective assessments and objective parameters shouldn't be extrapolated, as the result of this will be of doubtful value.
3. Driveability issues

[11] found a relation between the subjective assessment during tip in maneuvers and percentage of overshoot in the acceleration trace and the rise rate (also called jerk). They concluded that smoothness and speed of response are important factors that influence the driver's assessment. Damping ratio and natural frequency correlations to driveability show the desire for rapid reduction and decay of acceleration oscillations. Back-out manoeuvres showed similar results and evidence was found that increasing delays caused lower ratings.

The mountings of the powertrain to the body of an automobile can have a significant effect on driveability [6]. If the dynamic properties are not designed to filter out powertrain vibrations, these can be transmitted to the vehicle's body and cause discomfort in the form of audible noise and perceptible vibrations.

[6] opts a technique of active engine torque control for reducing vehicle shuffle by means of a feed-back-controller (based on pole-placement). The controller is designed to react strongly in the vicinity of the shuffle frequency and to introduce more damping. It generates a counter-acting torque, to compensate drivetrain oscillations. No additional sensors or actuators for implementations would be needed. The acceleration is estimated from the engine speed. Simulation results show a diminishing to 25% of the original oscillations.

Lock-up clutches used in torque converters of automatic transmissions are usually equipped with a torsional damper. When the lock-up clutch is open, the torque converter acts as a viscous damper, so that engine vibrations are not transmitted to the rest of the powertrain. With a closed lock-up clutch, even with a torsional damper, vibration problems are quite probable, due to an extended (lower engine speed) range in which the lock-up is closed, to obtain a lower fuel consumption [15].

[8] explains that low frequency fore and aft vibrations (surge) arise due to cycle-to-cycle variations of engine torque with low frequency, which causes abnormal (torsional) vibrations in the powertrain. Human sensitivity to fore-aft vibrations is highest below 10 Hz.
4. Driveability of CVT cars

Looking at an engine's torque map, the engine operates most efficiently along its maximum efficiency line (E-line) [16]. To operate the engine closer to its E-line, more gears are added to (especially automatic) transmissions. A Continuously Variable Transmission (CVT) can realize an infinite number of gear ratios, in a fixed range. So if the CVT's range is large enough, the E-line should be maintainable, since any wheel torque and speed can be converted into a point onto the E-line for the engine.

A problem arising during cruising when a tip-in (transient) maneuver is demanded. The car will drive at low engine speed with high overdrive ratio, until suddenly a large torque is demanded. The E-line demands a higher engine speed, which cannot promptly be realized due to the counteracting inertias of the engine and powertrain. Even if the E-line would be abandoned and the engine would be operated along its Wide Open Throttle line (WOT), the extra torque doesn't suffice, since the engine is already being operated near its maximum torque capacity.

To obtain a fast increase in engine speed, the CVT must be downshifted rapidly. Fast downshifting not only causes the engine to accelerate, it also extracts additional power from the vehicle's inertia, thus decelerating it. When the engine is up to speed, the car finally starts to show a persistent acceleration. This type of transient is also called "jet-start".

This means that the response of a CVT vehicle in a transient maneuver like this will show stumbling (inverse response) and hesitation, which are very undesirable phenomena with respect to driveability.

An option would be to keep the engine speeds higher during cruising, but this would diminish the gains in emission and fueling reductions.

4.1 Pulley ratio change

The change of the pulley ratio (di/dt) of a CVT is very important in the driveability rating of a CVT powered car. [15]

The objectives of a powertrain controller should therefore be magnitude AND smoothness (jerk) of the vehicle acceleration during a pulley ratio change.

If di/dt is large (figure 4.1), the vehicle will initially decelerate, as the kinetic energy of the vehicle is used to rev up the engine. When the pulley ratio is set and the engine is up to speed, an acceleration with large jerk will follow.

If di/dt is small, the acceleration will be very smooth, but the magnitude of the acceleration will be too small (figure 4.3).

With an optimally chosen di/dt the vehicle will not decelerate, and accelerate with few jerks. A period of hesitation remains (figure 4.2).

This implies a compromise is necessary for the pulley ratio change di/dt. This ratio change could be made adaptable to the driver's preference.
4.2 Delay time

The phenomenon of too fast downshifting causes a response with a dead time, or even an inverse response, which are very undesirable phenomena if the driver-vehicle is considered as a closed-loop control system (figure 4.4).

At virtually unchanged driver parameters the closed loop even might turn instable. This demands enormous workloads of the driver and even might result in hazardous traffic situations or at least irritation.

![Figure 4.4: The driver-vehicle closed-loop system](image)

4.3 Sound feedback

Continuously variable transmissions feature varying vehicle speed with (almost) constant engine speed. Initial responses of drivers showed that this phenomenon leads to comments like "poor performance feel" [17]. This can be explained by the fact (amongst others) that the drivers missed the sound feedback of acceleration of a conventional manual or automatic transmission. Extensive market research appraisal revealed, that however the phenomenon was noticed, most drivers felt that they could get used to it quickly.

4.4 Controllability

[17] found in market research that drivers of manual transmissions complained about lack of controllability, as the gear ratio of a CVT could not be changed manually. However, drivers of automatic transmission equipped vehicles found that the CVT characteristics were superior to the conventional automatic gearboxes.

4.5 Powertrain controllers

In [3] the design considerations of an engine controller structure for a diesel and CVT powered vehicle include reducing the demands on emissions and economy during transient manuevres to increase driveability. This means deviating from the e-line. [17] suggested that the use of electronic control facilitates the use of different control strategies by the driver. For example a "sport" and an "economy" setting. This way the driver can choose his/her own compromise regarding fuel consumption, performance and driveability.
4.6 Driveability of CVT cars at low vehicle speeds

In [10] and [12] a driveability rating of several vehicles is determined subjectively and objective data is measured simultaneously using 12 different test drivers and 5 different CVT equipped and one 4-speed automatic transmission. The tests considered concentrate very much on the first one to three seconds of the test.

The criteria to test are:
- Launch feel
  Starting from rest with mainly large pedal movements.
- Overall performance feel
  Starting from a velocity of around 12 km/h, the the pedal is depressed to its maximum position to have the cars provide maximum performance quickly.

The selected objective parameters used for a correlation analysis with the subjective data are:
- Delay time
  The time between a first change in pedal position and the first change in the acceleration trace
- Acceleration value
  The peak value of the initial acceleration phase
- Jerk Value
  The value of the initial acceleration divided by the duration of the initial acceleration to give the rate of change of acceleration during the initial phase of the test

The measurements taken included engine and vehicle speed, vehicle acceleration and pedal position.
The subjective data was collected using questionnaires with ratings from 1 to 10.

Results for launch feel:
There was a clear correlation between delay time and launch feel. Also a clear correlation was found for initial acceleration. No clear correlation was found for jerk and launch feel assessment.
The 4AT vehicle excelled in launch feel assessment, this was the only vehicle equipped with a torque converter. Concluding this test shows the differences between starting devices.

Performance feel:
Here was a good correlation between delay time and performance feel observed. Also a very strong relation is observed for initial acceleration value.

A CVT vehicle with electronic transmission control showed the best performance, and a torque converter as a startup device gave best launch feel.
5. The ZI powertrain

The ZI powertrain [16] consists of a metal pushbelt CVT that is coupled by means of a planetary gearset.

The engine and the wheels are coupled by means of the continuously variable transmission. This now entails that when the engine is at low speed relative to the wheels, the flywheel is at high speed. When during a sudden kick-down transient the engine needs to be accelerated rapidly, the flywheel is decelerated, with the wheels getting instant power with the engine at speed. The inertia of the flywheel virtually cancels out the inertia of the engine. This means the response time is dramatically improved, and the major portion of the CVT-associated dead time is cancelled, and no inverse response remains. This phenomenon is most pronounced at intermediate speeds (50 to 100 km/h). At low speeds (<50 km/h) the CVT cannot shift down far enough, due to its limited range. At high speeds, the engine is already at higher speeds, to obtain enough power for maintaining such high speeds.

A torque converter is used as a startup device. The accelerator pedal is decoupled from the engine’s throttle valve through a drive-by-wire system. This complete powertrain approach makes it viable to let the engine operate at its maximum efficiency line (E-line), which is characterised by high torques, at low engine speeds. This can now be done without sacrificing driveability, as will be shown.
6 ZI driveability at low speeds

An attempt is made to use a simulation model of the vehicle equipped with the ZI powertrain for prediction of the driveability for "Launch feel" and "Performance feel" criteria as set out in [12].

The input for a full-throttle tip-in manoeuvre was chosen as in figure 6.1 with a period resembling the fastest throttle position changes in [11]. This proved not necessary, a simulation with a step input as pedal position produced a very similar response, concerning the amplitude of the fore- and aft acceleration trace, only a slightly faster build-up of the initial acceleration.

The simulation model is based on the powertrain of the vehicle with torque converter, CVT and controller, and the engine as an engine speed-torque map. The controller makes sure the E-line is followed.

6.1 Launch feel

A simulation with the vehicle starting from rest with maximum throttle was performed. The result is shown below.
This acceleration trace starts with a second order-like response, then when reaching the maximum acceleration, it shows some oscillations. This is due to powertrain oscillations (especially the drive shafts). Considering this first part of the acceleration as a first order response together with a delay time, the resulting delay time would be 0.01 [s]. However, since the engine is not modeled with two discrete ignitions per revolution, and the engine would be idling (900 rpm) at the moment of tip-in one revolution would take 60/900=0.067 s. So the time between two combustions is: 60/(900*2)= 0.0083. Let’s assume the engine would take about one to one revolutions to respond, the delay would be about 0.1 [s].

<table>
<thead>
<tr>
<th>Delay Time</th>
<th>0.01 to 0.1 [s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acceleration</td>
<td>3.6 [m/s²]</td>
</tr>
</tbody>
</table>

Table 6.1: “Launch feel” parameters

Using figure 6.3 [12], we can predict the driveability for the ZI vehicle. Since driver’s perception can get nonlinear for severe manuevers, a linear fit like this is of very doubtful value outside of the fitted region. The delay time is outside of the fitted range, but from the previous chapters we can still conclude that a shorter delay time is better with respect to driveability. Looking at figure 6.3, the driveability prediction for Launch feel based on the delay time should be larger than 8 (on a scale from 1 to 10). Based on the initial peak of acceleration, which is also outside the fitted range, the driveability rating should be over 8.5. Further, the ZI car outperforms all of the vehicles tested in [12]. This is due to its torque converter characteristics, as the best performing tested car in this category was also equipped with a torque converter.

7.2 Performance feel

The performance category tests had starting velocities on around 12 km/h. The simulation results (figure 6.4, table 6.2 and figure 6.5):
The delay time again lies outside of the fitted range, so it would predict a driveability of over 8. Based on the maximum value of the acceleration, the driveability prediction would be 7.3. Based on Jerk, a rating over 8.5 is predicted.

Compared to the other cars of [12], the car performs just above average. This would imply the maximum acceleration value is the limiting factor. The lowest ratio of the CVT limits the engine speed obtainable at this speed. The ZI's CVT cannot downshift much, so the ZI-effect is not very pronounced at this speed (figure 6.4 compares the CVT and the ZI). The lock-up clutch of the torque converter is not yet closed at this speed, so the torque converter determines the acceleration response.
7. ZI driveability at higher speeds

The torque converter’s lock-up clutch is closed (dependent on a number of powertrain conditions) at speeds above about 15 km/h, so the engine is now directly coupled to the rest of the drivetrain. This implies that the damping properties of the torque converter are lost (but also its viscous energy losses), so that (engine) vibrations are more easily transmitted to the rest of the drivetrain and vehicle. Below the results for kickdown manoeuvres starting at speeds of 30, 50 and 80 km/h are presented. At each speed a simulation for the ZI equipped vehicle are plotted, together with a CVT (ZI without flywheel), and the experimental results of the CVT vehicle (ZI without flywheel). Experimental results of the ZI are not available at this point, but should be evaluated later.

The experimental fore- and aft acceleration trace is reconstructed by means of a Kalman filter from the powertrain’s wheel torque and wheel speed. In fact this is the acceleration of the drive shaft at the differential and this cannot be set equal to the acceleration trace to the acceleration trace of the body due to damping in the tires and body compliances. When measuring the ZI’s acceleration traces for driveability purposes, more accurate measurements could be obtained by measuring the fore-aft accelerations directly from the vehicle’s passenger compartment.

7.1 Kickdown at 30 km/h

![Acceleration graph](image)

*Figure 7.1: Accelerations from 30 km/h*

From a starting vehicle speed of 30 km/h, the CVT starts with an initial increase of acceleration (figure 7.1), which quickly drops down to a point where the vehicle decelerates, as the energy extracted from the vehicle is bringing the engine up to speed, as the CVT is shifting down. Then the vehicle starts to accelerate again, when the engine is up to speed, ending in a peak at 2.2 s, when the CVT has finished shifting down. After that time the CVT gradually shifts up again.

The ZI has a higher initial acceleration increase, which drops down also, but it maintains a positive acceleration. The engine is brought up to speed, not by slowing down the vehicle, but by extracting energy from the flywheel. The rest of the acceleration trace is quite similar to that of the conventional CVT.
The experimental kickdown manoeuvre shows stretchiness compared to the simulated CVT. Especially between 0.5 and 3 seconds the acceleration is significantly lower than predicted in simulation. This is mainly due to actuation hardware limitations in shifting speeds between the model and the real vehicle (figure 7.2). As the simulation model downshifts faster, the engine can deliver more power at higher engine speeds. Shuffle is present, mainly caused by the driveshafts (figure 7.1). It increases as time moves on. This is because the CVT is shifting down, and for lower ratios, the apparent mass of the engine, as felt at the driveshafts gets higher. The resonance frequency consequently gets smaller at a higher magnitude.

![Figure 7.2: Experimental and simulation CVT ratios compared](image)

### 7.2 Kickdown at 50 km/h

The CVT responds in a similar manner as to when starting at 30 km/h (figure 7.3). The peak when the CVT has finished downshifting is gone, because the shifting
occurs different. It has an initial period of about 0.5 s with very little acceleration, and oscillations.
The ZI responds promptly with a peak of 1.5 m/s² and shows less sag after the initial peak of acceleration.
Again the experimental results of the CVT do not match the simulation well. Again, the “real” CVT downshifts slower. Drivetrain-generated oscillations again increase with downshifting.

7.3 Kickdown at 80 km/h

The CVT again has a hesitation period of about 0.5 s.
The ZI still shows less sag after the initial peak of acceleration.
The experimental results match the simulation results of the CVT better, mainly used by faster downshifting compared to previous experiments.

7.4 Conclusions

The ZI outperforms the CVT (ZI without flywheel) at every speed. The ZI has a very short to no delay at all, opposed to the CVT, that shows a delay of 0.5 s, more pronounced at higher speeds. The ZI performs better as the speeds increase, because at lower speeds it cannot downshift as far, because of the ratio limit of the CVT. Powertrain oscillations play a more distinct role in experimental results than in simulation. These are more distinct at lower powertrain ratios. These results confirm that downshift speed plays a mayor role in establishing the resulting acceleration trace.
The experimental results of the CVT do not correspond with the simulations well. This is mainly caused by differences in shift strategy. The final ZI version will have the same shifting pattern, so the differences between the simulated CVT and ZI are comparable to the experimental differences, concerning the qualitative phenomena.
8 Ride comfort

8.1 Introduction
Since improved driveability and fuel economy should not degrade the ride comfort of the vehicle, further analysis is necessary. Using the same simulation tool as before, vibrations caused by the ZI-vehicle's powertrain are analysed and compared with the original 4-speed automatic powertrain.

8.2 International standard ISO 2631-1

Introduction
The International Standard ISO 2631-1: Mechanical vibrations and shock - Evaluation of human exposure to whole-body vibration - [18] will be used to quantify vibration and shock comfort as a part of this driveability study. This analysis is based on the acceleration trace a human is subjected to. The fore and aft accelerations of the vehicle as rigid body will be analysed, derived from powertrain torques, so the effect of vehicle body vibrations and seat (-rail) dynamics are not taken into account, as found previously. Analysis of tip in manoeuvres at speeds of 50 and 80 km/h will be considered. These will be compared with previously measured accelerations (reconstructed from drivetrain torque traces as well) from the unmodified vehicle, equipped with a 4 speed automatic transmission.

Weighting
The acceleration trace will first be weighted using frequency-based filters, representing the human sensitivity to vibrations and shocks. The filters of interest here (fore-aft) are \( W_d \) for the seat-surface and \( W_e \) for the seat-back. Both filters are band pass, between 0.4 and 100 [Hz]. Further there is an acceleration-velocity transition (proportionality to acceleration at lower frequencies, proportionality to velocity at lower frequencies, for \( W_d \) at 2.0 [Hz] and for \( W_e \) at 8.0 [Hz]

![Surfaces of interest](image)

*Figure 8.1: Surfaces of interest*
The associated transfer functions are:

\[ W_d(s) = \frac{s^2}{s^2 + 0.8\sqrt{2} \cdot \pi \cdot s + (0.8\pi)^2} + \frac{1}{\left(\frac{1}{200\pi}\right)^2 s^2 + \frac{\sqrt{2}}{200\pi} s + 1} + \frac{1}{4\pi s + 1} \]

\[ W_e(s) = \frac{s^2}{s^2 + 0.8\sqrt{2} \cdot \pi \cdot s + (0.8\pi)^2} + \frac{1}{\left(\frac{1}{200\pi}\right)^2 s^2 + \frac{\sqrt{2}}{200\pi} s + 1} + \frac{1}{16\pi s + 1} \]

**Rating criteria**

**R.m.s. method**

r.m.s. acceleration is defined by:

\[ a_{\text{rms}} = \left[ \frac{1}{T} \int_0^T a_w(t) \, dt \right]^{\frac{1}{2}} \quad (8.1) \]

with

\[ a_{\text{rms}}(t) \] the weighted acceleration \([\text{m/s}^2]\)
\[ a_w(t) \] the weighted acceleration \([\text{m/s}^2]\)
\[ T \] the duration of the measurement \([\text{s}]\)
\[ t \] the time (integration variable) \([\text{s}]\)

The crest factor is defined as:

\[ \text{crest factor} = \frac{\text{max}[a_w(t)]}{a_{\text{rms}}} \quad (8.2) \]

If the crest factor is below 9, determining of \(a_w\) is normally sufficient. However for higher crest factors or other reasons why \(a_w\) would underestimate the severity of the vibration, one alternative measure needs to be determined as well.
Running r.m.s. method

\[
a_{\text{rrms}}(t_0) = \left( \int_{t_0}^{t_0+\tau} |a_w(t)|^2 \, dt \right)^{\frac{1}{2}}
\]  

(8.3)

with

\[a_{\text{rrms}}(t)\] the running r.m.s. acceleration [m/s²]
\[a_w(t)\] the weighted acceleration [m/s²]
\[\tau\] the integration time for running averaging [s] (recommended \(\tau=1\) [s])
\[t\] the time (integration variable) [s]
\[t_0\] the time of observation [s]

This method better takes occasional shocks into account. The maximum transient vibration value is defined as

\[MTVV = \max(a_{\text{rrms}}(t_0))\]  

(8.4)

Fourth power vibration dose

Further there is the fourth power vibration dose value, with a similar definition to formula 8.1, only the weighting occurs with the fourth power instead of squaring the signal.

\[VDV = \left[ \int_{t_0}^{t_0+\tau} |a_w(t)|^4 \, dt \right]^\frac{1}{4}\]  

(8.5)

This method is therefore more sensitive to peaks.

Since the following measurements deal with occasional peaks/shocks and high crest factors (up to 12), both the running r.m.s. method (MTVV) and the fourth power vibration dose (VDV) have been taken into account. Since the signals considered here show mostly occasional shock (no periodic behaviour), MTVV is most of interest.

8.3 Comfort during kick-down accelerations

To evaluate the discomfort, kick-down simulations of the ZI-equipped car have been compared with experimental data of the same car with its 4 speed automatic drivetrain (4AT). The acceleration trace of the 4AT has been reconstructed from torque measurements and wheel position measurements using a kalman filter.

The speeds for which the acceleration data have been compared are 50 and 80 km/h. This is where the Zi-phenomenon is most pronounced, and where accelerations are highest. The results are shown below.

Kickdown at 50 km/h

First the 4-speed automatic will be assessed. The hesitation cannot be compared since the time of the initial throttle pedal of the 4AT is unknown. It is not important in this comfort comparison.
The acceleration trace of the AT4 shows an initial peak of about 1.25 (m/s²). This is solely caused by opening the throttle on third gear (and possibly opening the torque converter to quickly rev up the engine). The powertrain is then starting the downshift from third to second gear. This shown up in the acceleration trace as a sag, followed by a second peak and a sharp stumble. When second gear is reached the acceleration remains fairly constant.

The ZI car starts with a sharp increase in acceleration. A slight sag is visible after the first peak, then the acceleration gradually increases.

The weighted accelerations are also presented. The “seat” measurements are the accelerations weighted with filter $W_d$ for the seat-surface and the “back” measurements are accelerations weighted with filter $W_e$ for the seat-back.

![Graph](image)

*Figure 8.4: Kickdown accelerations at 50 km/h*

The ZI has one major peak due to the initial increase of acceleration, followed by a peak due to the settling of the acceleration trace. After that few more contributions are generated. The AT has about the same peak for the initial acceleration increase. However, the gear shift shocks keep generating extra peaks in the weighted acceleration trace.

Further, the higher frequency of the acceleration-velocity transition of the $W_e$ filter is clearly visible, since higher frequency compounds cause higher peaks in the back evaluations seat-surface evaluations.
The evaluation parameters are visualized above (figure 8.5). The AT4 has a higher rating than the ZI for all three parameters. This is due to the AT’s shift related shocks. Further the AT has higher ratings for the seat-back that its ratings for seat-surface, because its acceleration signal contains more higher frequency shocks than the ZI, which does barely show this difference in weighting filters. Concluding the ZI is about 20% less uncomfortable than the AT4 at 50 km/h.

There is a distinct difference in the discomfort of the initial acceleration peak, and following peaks / discomfort contributions. The first peak is the result of a step input by the user, and is anticipated by the driver. Therefore the first peak (which constitutes the main discomfort for the ZI defined by the ISO-norm) should be subtracted from the subsequent accelerations. This would mean that the relative difference between the comfort of the ZI and the AT would be significantly larger.

For comparison a step acceleration signal has been added to this analysis, of step height 1.8 m/s². It only contains an initial shock. The step’s $a_{rms}$ would be the lowest value possible to obtain such a response, if the first peak would not be taken into account. Taking this as a base-line value, the difference between the AT and ZI is over 50%.

**Kickdown at 80 km/h**

The AT shows an initial peak (figure 8.6), than some sag and a period of constant acceleration (0.25 s to 0.75 s). Then a series of peaks and stumbles when downshifting to third gear, followed by a short period of constant acceleration (1.35 s to 1.6 s). Another series of peaks and stumbles when downshifting to second gear, followed by some obvious drivetrain oscillations (shuffle), and after 2.3 s again a period of constant acceleration. Compared to the kickdown at 50 km/h, the AT4 shows overshoot at the end of a backshift. It is also clear that because the gear ratio gets shorter (peak at 1.3 s compared with peak at 2 s), drivetrain oscillations are transmitted more.
The ZI powertrain shows a similar response as for the 50 km/h kickdown, but now the initial peak value of the acceleration is higher relative to the acceleration at the end of the window.

![Acceleration 80 km/h](image)

Figure 8.6: Kickdown accelerations at 80 km/h

As the acceleration trace of the ZI is similar to that of 50 km/h, the weighted acceleration trace is similar as well.

More gear shifts cause more peaks in the weighted acceleration trace of the 4AT.

![Evaluation of shocks at 80 km/h](image)

Figure 8.7: Evaluation of shocks at 80 km/h

The difference between the evaluation parameters of the ZI and AT4 are larger at 80 km/h compared to those at 50 km/h. This is mainly caused by an extra gear shift of the AT.

Again a step acceleration has been added for comparison.

Concluding the comfort of the ZI is 50 % better compared to the AT4. Without rating the initial peak, the ZI’s advantage again would be greater.
9. Proposed driveability tests

The driveability tests preferably should be standardized tests, alike the CEC M-08-T-83 Cold weather driveability test procedure [19] (figure 9.1) or the CEC M-09-T-84 Hot weather driveability test procedure. The advantage of these tests is that there is reference material available. Another example (in the form of step-by-step instructions) [14] is given in Appendix 1.

Since the CEC M-08-T-83 Cold weather driveability test procedure doesn’t comprise all possible driving manoeuvres, a number of additional test would be needed:

- WOT accelerations from a range of speeds (e.g. 0, 30, 50, 80, 100 km/h) to simulate emergency accelerations. Hesitation, stretchiness and stumbles are well identifiable during these tests.
- Traffic following, at low speeds (simulating traffic jam), and intermediate speeds (driving through town). These test where another vehicle is followed at a short distance clearly shows driveability for low accelerator pedal movements, but high demands as for the driver-vehicle control loop. This is because the CEC tests demand the driver to focus on maintaining a speed trajectory, whereas in traffic following, a distance between the two vehicles needs to be maintained constant. Hesitation is rated severely during these tests.

Further, since shuffle is not rated in the CEC test [19], extended demerit and weightings tables including shuffle can be used as in tables 9.1 and 9.2.

The measurements to be taken should at least comprise:
- pedal position
- vehicle acceleration
- vehicle speed
Test driver’s ratings/comment should be gathered during the experiment in a similar manner to Appendix 1, and evaluation forms should be filled out after the tests.

Total demerits should then be calculated, and the gathered data analysed.

<table>
<thead>
<tr>
<th>Malfunction</th>
<th>Each occurrence</th>
<th>Trace</th>
<th>Moderate</th>
<th>Severe</th>
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<td>Stall at start</td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Idle stall</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Driving stall</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Idle quality</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>Hesitation</td>
<td>1</td>
<td>3</td>
<td>6</td>
<td></td>
</tr>
<tr>
<td>Stumble</td>
<td>1</td>
<td>3</td>
<td>6</td>
<td></td>
</tr>
<tr>
<td>Backfire</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>Surge</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>Shuffle</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td></td>
</tr>
</tbody>
</table>

*Table 9.1: Extended ECE malfunction demerits [19]*

<table>
<thead>
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<th>Malfunction</th>
<th>Weighting</th>
</tr>
</thead>
<tbody>
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</tr>
<tr>
<td>Idle stall</td>
<td>7</td>
</tr>
<tr>
<td>Driving stall</td>
<td>42</td>
</tr>
<tr>
<td>Idle quality</td>
<td>1</td>
</tr>
<tr>
<td>Hesitation</td>
<td>4</td>
</tr>
<tr>
<td>Stumble</td>
<td>4</td>
</tr>
<tr>
<td>Backfire</td>
<td>4</td>
</tr>
<tr>
<td>Surge</td>
<td>3</td>
</tr>
<tr>
<td>Shuffle</td>
<td>3</td>
</tr>
</tbody>
</table>

*Table 9.2: Extended ECE malfunction weightings [19]*
10. Conclusions

10.1 End results of this report

After a study of literature available on the subject of driveability, driveability and its phenomena have been explained, and a number of issues of general kind and applicable to CVT-equipped vehicles have been addressed.

An attempt has been made to assess driveability for the Zero-Inertia vehicle, equipped with a CVT and a power-assist in the form of a flywheel.

Low speeds:
- When starting from rest, the ZI car outperforms all of the CVT and AT vehicles tested in [12]. The driveability rating predicted is above 8 on a scale from 1 to 10.
- At a speed of 12 km/h, the car is stuck at a driveability rating of 7.3, limited by its maximum acceleration value. Compared to the other cars of [12], the car performs just above average.

Higher speeds:
- At starting speeds from 30, 50, and 80 km/h, the ZI outperforms the CVT at all speeds, especially at reducing the dead time from 0.5 [s] to 0.1 [s], and eliminating inverse responses.

Ride comfort
- At 50 km/h the ZI reduces the discomfort compared to its original 4-speed automatic gearbox with at the very least 20 %, at 80 km/h the ZI even performs over 50 % better.

10.2 Suggestions for further investigation

Some measurements of the ZI without flywheel (reported as experimental CVT results) have been already reported here. When the ZI-equipped car is ready for testing including its flywheel, a final driveability rating can then be determined, including test drivers' judgements. Suggestions for these assessments have been given.

The definitive comparison can be made between the CVT and the ZI, and the simulation results of the ZI validated.
References


Appendix 1  Step by step instructions example [14]

Step-by-step instructions for the "CRC COLD-START AND WARM-UP DRIVEABILITY CYCLE"

1) Turn the key to "on" (NOT start) for two seconds to prime the fuel system.

A) Start vehicle in park according to Owner's Manual Procedure
   a) If the vehicle starts in 5 seconds or less, record starting time as the first starting tune box.
   b) If the engine stalls during the 5 second idle, record a stall in the idle-in-park stalls section, turn the key to off and proceed with step 1 B.
   c) If vehicle fails to start in 5 seconds, record NS in the first starting tune box and turn key off, continue with step 1 B.

B) Attempt to start as in step A.
   a) If the vehicle starts in 5 seconds or less, record starting time in the second starting tune box.
   b) If the engine stalls during the 5 second idle, record a stall in the idle-in-park stalls section, turn the key to off and proceed with step 1 C.
   c) If vehicle fails to start in 5 seconds, record NS in the second starting tune box and turn key off, continue with step 1 C.

C) Attempt to start as in step A.
   a) If the vehicle starts in 5 seconds or less, record starting time in the third starting tune box.
   b) If the engine stalls during the 5 second idle, record a stall in the idle-in-park stalls section, turn the key to off and then start the vehicle as many times as possible. Proceed to step 2.
   c) If vehicle fails to start in 5 seconds, record NS in the third starting tune box and turn key off, then start the vehicle as many times as possible. Proceed to step 2.

2) A) Once started, apply brakes and shift into overdrive (or drive if overdrive is not available) for 5 seconds. Evaluate the idle quality during this period and record it.
   B) If engine stalls, record the event and restert in most efficient manner. Do not record restart time. Only the first stall is counted in decimals. Go to step 3.

3) A) Make a 0-15 MPH (0-25 kph) snap & hold, light-throttle acceleration. Record the severity of all malfunctions and the occurrence of stalls. Stop: Idle 3 seconds but do not rate it.
   B) Make a second 0-15 MPH (0-25 kph) snap & hold, light-throttle acceleration. Record the severity of all malfunctions and the occurrence of stalls.
   NOTE: Both these accelerations are to be accomplished in the first 0.1 mile (161m), if they are completed over a shorter distance, cruise at 15 mph (25 kph) to that mark.

4) Stop at the 0.1 mile (161m) mark and idle for 3 seconds do not rate it. Make a 0-20 mph (0-32 kph) snap & hold, slow-open-throttle acceleration. Decelerate to 10 mph (16 kph) and cruise to the 0.2 mile (322m) mark. Record the severity of all malfunctions and the occurrence of stalls.

5) A) Start at the 0.2 mile (322m) mark and idle for 3 seconds do not rate it. Make a 0-15 MPH (0-25 kph) snap & hold, light-throttle acceleration. Record the severity of all malfunctions and the occurrence of stalls. Stop: Idle 3 seconds but do not rate it.
   B) Make a second 0-15 MPH (0-25 kph) snap & hold, light-throttle acceleration. Record the severity of all malfunctions and the occurrence of stalls. Both these accelerations are to be accomplished within 0.1 mile (161m), if they are completed within a shorter distance, cruise at 10 mph (16 kph) to the 0.3 mile (484m) mark. Do not stop.

6) At the 0.3 mile (484m) mark make a 10-20 MPH (16-32 kph) snap & hold, light-throttle acceleration. Record the severity of all malfunctions and the occurrence of stalls. If the maneuvers do not require the entire 0.1 mile (161m), cruise at 10 mph (16 kph) to the 0.4 mile (644m) mark.

7) Stop at the 0.4 mile (644m) mark and idle for 3 seconds do not rate it. Make a 0-20 mph (0-32 kph) snap & hold, moderate-throttle acceleration. Proceed to the 0.5 mile (805m) mark.

8) On short tracks, turn the vehicle around to make a repeat pass. Idle for 5 seconds and evaluate the stall.

9) Repeat steps 3-7. Distances within step 9 refer to the distance from the point where step 8 occurred.

10) On short tracks, turn the vehicle around in order to perform step 3-13 over the same course used for steps 3-7. Idle for 5 seconds and
11. Mix a constant vacuum crowd acceleration from 0-45 mph (0-72 kph) and then use moderate braking to reach 25 mph (40 kph). This maneuver is to be accomplished at 0.4 miles (644m). Record the severity of all malfunctions and the occurrence of stalls.

12. At the 0.4 mile (644m) mark make a 25-35 mph (40-56 kph) snap & hold, accelerate and stop at the 0.5 mile mark. Record the severity of all malfunctions and the occurrence of stalls.

13. Idle for 30 seconds and evaluate the idle at 5 and 50 seconds. This completes the test.

Definitions:
- Light Throttle: constant throttle position and associated manifold vacuum required to accelerate from 0-25 mph (0-40 kph) in exactly 9 seconds when the engine is cold.
- WOT: defined as the manifold vacuum when the accelerator pedal is pushed to the floor. This value is not 0 in some vehicles.
- Moderate Throttle: as defined as an initial manifold vacuum that is the mean of the light throttle and WOT manifold vacuums.
- Cold: a constant vacuum acceleration performed at the initial manifold vacuum for light throttle accelerations.
- Distant accelerations are accomplished with the manifold vacuum that just prevents downshift at 25 mph (40 kph) with a cold engine; this is a constant throttle position acceleration.

Snap & Hold accelerations are performed by immediately depressing the accelerator pedal to the position that generates the required vacuum and held at that position regardless of subsequent changes in speed or manifold vacuum. This requires practice with each vehicle to be tested.

Malfunctions:
- Stalls: Engine ceases to run.
- Hesitation: A temporary lack of power immediately upon throttle opening that is not characteristic of the vehicle’s warmed up performance.
- Stumble: A temporary reduction in power after throttle opening.
- Surges: A random decrease and increase in power.
- Backfire: An “explosion” in either the intake or exhaust system.
- Idle roughness: An evaluation of idle quality and smoothness based on vibration in the seat, steering wheel, armrest, and also the sound. The worst idle quality during the evaluation time should be recorded.

Severity Levels:
- Trace: Just noticeable to ears and unlikely to be noticed by most laymen.
- Moderate: A level of severity readily noticeable by most laymen.
- Heavy: Pronounced malfunctions that would be obvious to any driver.
- Extreme: Severe malfunction likely to cause the laymen to real driving to discontinue the maneuver in favor of some other action.

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