Study of Objective Assessment Indexes of Shuttle Shift Quality of Wheel Loader

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Abstract. The objective assessment indexes of shuttle shift quality of wheel loader are investigated. The process of shuttle shift is divided into two stages. At the deceleration stage, a large jerk value is observed, and a maximum acceleration value is reached when the shuttle clutch is synchronized. At the acceleration stage, the jerk is too small to be an index of comfortableness. The maximum acceleration, vibration dose value (VDV) and jerk of deceleration stage show a good linear correlation, meaning that the three indexes have similar representative ability for comfortableness assessment. The total duration of shuttle shift is chosen as an index because it is directly related to working efficiency. The duration, in which the torque converter plays a dominant role, is more than 50\% of the total duration of shuttle shift, indicating that the duration of shuttle shift is mainly determined by torque converter’s characteristics. The overshoot distance is chosen as the index to represent the dimensional behaviour of the shuttle shift.

1. Introduction

The qualities of star-up, gear shift and shuttle shift are main performance behaviours of vehicle transmission system. In the traditional way, these qualities are evaluated by expert drivers. An overall rating is obtained based on ratings of certain number of drivers and certain defined test conditions. This assessment method mainly relies on the experience of the drivers. To eliminate the personality during such evaluation, an objective assessment is considered to be the solution \cite{1}.

For quality assessment of start-up and gear shift of vehicle transmission, comfortableness and time duration have been considered as two main aspects \cite{2-6}. For comfortableness assessment, acceleration amplitude, jerk and vibration dose value (VDV) calculated based on chassis acceleration data are commonly used. For time duration assessment, the duration of each stage of gearshift is used. In order to have more comprehensive assessment, besides above indexes, engine speed, fuel consumption and emission are put into consideration \cite{7-11}.

For working vehicle, besides start-up and gear shift, shuttle shift is also commonly used, especially for wheel loader. At shovelling and loading operation of wheel loader, four times of shuttle shift are used per work cycle. Thus, the quality of shuttle shift is an important behaviour of wheel loader. Previous studies mainly focus on the assessment of star-up and gear shift in driving vehicle, and minor
study is found to focus on the shuttle shift. In this study, the process of shuttle shift of wheel load is tested, and objective assessment indexes of shuttle shift quality are investigated from aspects of comfortableness, duration and dimension.

2. Experimental method
The main specifications of test wheel loader are shown in table 1. The wheel loader has a power shift transmission, which is constituted of a hydrodynamic torque converter and a gearbox with four forward and three reverse speeds. The gear ratios are shown in Table 2. The driving direction is controlled by a KV and a KR clutch. During shuttle shift from forward to reverse, the KV clutch disengages and KR clutch engages. During shuttle shift from reverse to forward, the clutches act oppositely. During shuttle shift, gear clutches are kept unchanged.

| Table 1. Main specifications of tested wheel loader |
|-----------------------------------------------|
| Weight with empty bucket: 20100 kg            |
| Weight with full bucket: 26100 kg             |
| Engine power: 180 kW                          |
| Transmission: Constituted of a hydrodynamic torque converter and a gearbox with 4 forward and 3 reverse speeds |
| Axle ratio: 24.7                               |
| Tire diameter: 1.5 m                           |

| Table 2. Gear ratios of the transmission of test wheel loader |
|-----------------------------------------------|
| Direction     | Gear level | Gear ratio |
|----------------|------------|------------|
| Forward        | 1<sup>st</sup> gear | 4.15       |
|                | 2<sup>nd</sup> gear | 2.09       |
|                | 3<sup>rd</sup> gear | 1.07       |
|                | 4<sup>th</sup> gear | 0.64       |
| Reverse        | 1<sup>st</sup> gear | 3.94       |
|                | 2<sup>nd</sup> gear | 1.98       |
|                | 3<sup>rd</sup> gear | 1.02       |

Tests are implemented on a flat road. A steel block with weight of 6 tonnage is put into the bucket to simulate the weight of full load condition. Consistent to real working operation, shuttle shift of first and second gears are tested. To have a consistent performance of engine, hydrodynamic torque converter and clutches, the engine cooling water temperature and transmission oil temperature are kept in the range of 80 °C to 90 °C. Recorded physical parameters are shown in Table 3.

| Table 3. Test parameters and methods. |
|---------------------------------------|
| Test parameter                      | Test device or method                       |
| Engine speed                        | Hall speed sensor                           |
| Engine acceleration pedal            | Angle sensor, obtained by CAN data          |
| Engine torque                       | Calculated by ECU, obtained by CAN data     |
| Turbine wheel speed                  | Hall speed sensor                           |
| Transmission output shaft speed      | Hall speed sensor                           |
| Longitudinal acceleration            | Dytran 7503D2 acceleration sensor, located on the chassis |
| Vehicle velocity                    | RACELOGIC VBOX 3i                           |
| Distance                             | RACELOGIC VBOX 3i                           |
| Shuttle level signal                 | Displacement sensor                         |

3. Characteristics of shuttle shift
As the characteristics of shuttle shift at both directions are similar, only shuttle shift from forward to reverse is discussed in this section. Engine acceleration pedal is kept unchanged during shuttle shift. Speeds of driving and driven clutches of KR clutch are calculated based on the turbine wheel speed,
output shaft speed and ratios of internal shafts of the gearbox. The engine rotating direction is defined as positive. So, negative speed value means that the rotation direction is opposite to the engine. The forward direction is defined as positive, and negative value of velocity means that the direction is reverse. Negative acceleration value at positive direction means that the vehicle is decelerating, and negative acceleration value at reverse direction means that the vehicle is accelerating.

As shown in Figure 1, the shuttle shift process can be divided into two stages. At the beginning, it is a deceleration stage, and after that it is an acceleration stage.

![Figure 1. Process of shuttle shift from forward to reverse at first gear and second gear](image)

The test result of first gear is shown in Figure 1.a. At the deceleration stage, after the KR clutch begins to engage, the speeds of driving discs and driven discs are dragged down dramatically. After the discs are synchronized, the vehicle velocity is decelerated to 0 m/s. The clutch keeps slipping during the whole period of the deceleration stage. Under the effect of slipping force, the speed ratio of torque converter drops to zero. The acceleration curve shows a significant slope and reaches a peak value when the discs are synchronized. At the acceleration stage, under the tractive effect of torque converter, the vehicle velocity increases to a stable value. As shown in Figure 2, the driving torque is decided by the characteristics of torque converter. Thus, at the acceleration stage, the torque converter plays a dominant role. As the tractive effect of torque converter is much gentler than that generated by clutch slipping, the acceleration curve shows a smaller slope. During the shuttle shift, the engine torque increases at the deceleration stage and then decreases at the acceleration stage. The engine speed drops a little at the deceleration stage and then increases to a stable value at the acceleration stage.

The test result of second gear is shown in Figure 1.b. At the deceleration stage, the speed of driving discs of KR clutch decelerates to 0 r/min and then oppositely accelerates until being synchronized with driven discs. At the same time, the torque converter enters into reverse mode (as shown in Figure 2), where torque converter has a braking effect to the vehicle. Inconsistent with the result of the first gear, the slipping effect of clutch discs are not able to brake the vehicle to 0 m/s. After the discs are synchronized, the torque converter becomes dominant in following process. Firstly, the torque converter brakes the vehicle to 0 m/s. And then, the torque converter accelerates the vehicle in an opposite direction to a stable velocity. At the deceleration stage, the acceleration curve also shows a significant slope and reaches the peak value when the discs are synchronized. The engine torque and engine speed show similar tendency with the results of the first gear.
4. Objective assessment indexes of shuttle shift

4.1. Indexes of comfortableness

Because jerk represents acceleration slope, it can eliminate the effect of bump and fluctuation caused by road. In previous studies, jerk has been widely considered as one main index of comfortableness. Vibration dose value (VDV) puts peak value, fluctuation and duration into consideration, which represents the integrated effect of acceleration to human body. Acceleration is also considered as index of comfortableness in the assessment of gearshift in automatic transmissions. As candidates for indexes of shuttle shift, these three indexes are discussed in this section. Two jerk values are investigated. $j_1$ is the jerk value generated at deceleration stage, and $j_2$ is the jerk value generated at acceleration stage. The absolute maximum acceleration value ($\alpha_{\text{max}}$) and VDV are calculated as shown in Figure 3 and Equation (1).

$$VDV = \left\{ \int |\alpha(t) - \alpha(t_0)|^4 dt \right\}^{1/4}$$

Test result of jerk of shuttle shift from forward to reverse is shown in figure 4. As velocity increases, the speed difference between driving discs and driven discs becomes larger. This results to increased slipping force, leading to larger $j_1$ values. According to the inner structure of the gearbox, the vibration caused by shuttle clutch is multiplied by gear ratio. Because the first gear has larger gear
ratio, the $j_1$ values of the first gear are bigger than the second gear. At a given velocity and gear, the
jerk is compromised by vehicle weight, showing smaller $j_1$ value at full load that empty load.

![Figure 4](image_url)

**Figure 4.** Result of jerks of shuttle shift from forward to reverse

According to the discussion in previous section, at the acceleration stage, the torque converter play
a dominant role. Because the tractive torque of torque converter is gentler, the $j_2$ is much smaller than
$j_1$. As referred to literature 1, a jerk value lower than 5 m/s$^3$ is not perceived by the driver. As shown
in Figure 4, all $j_2$ values are much lower than 5 m/s$^3$. Thus, the jerk generated by the torque converter
in the acceleration stage is not suitable as an index of comfortableness.

Test results of $\alpha_{\text{max}}$ and VDV of shuttle shift from forward to reverse are shown in Figure 5. As
velocity increases, $\alpha_{\text{max}}$ and VDV show a raising tendency. Compared to first gear, the $\alpha_{\text{max}}$ and VDV
of second gear are smaller. Compared to empty load, the $\alpha_{\text{max}}$ and VDV of full load are lower. The
$\alpha_{\text{max}}$ and VDV show similar tendency with $j_1$.

![Figure 5](image_url)

**Figure 5.** Result of $\alpha_{\text{max}}$ and VDV of shuttle shift from forward to reverse

The correlations among $\alpha_{\text{max}}$, $j_1$ and VDV are shown in Figure 6. As reported in previous study [1],
VDV is sensitive to peak values and fluctuations. As shown in Figures 1, no fluctuation around $\alpha(t_0)$
is shown, and $\alpha_{\text{max}}$ is the only peak value. Thus, according to Equation (1), VDV and $\alpha_{\text{max}}$ show a
good linear correlation. As shown in Figure 1, the acceleration shows a very linear change from $\alpha(t_0)$
to $\alpha_{\text{max}}$. Because $j_1$ represents the slope of acceleration curve, and $\alpha(t_0)$ is near to 0 m/s$^3$, $j_1$ shows a
good linear correlation with $\alpha_{\text{max}}$. 

5
Based on above discussion, it can conclude that due to the own characteristics of shuttle shift, $\alpha_{\text{max}}$, $j_1$ and VDV show a good linear correlation. Thus, the three indexes have similar representative ability for comfortableness assessment. Because the values of $j_2$ are too small to be perceived by the driver, it is not suitable as index of comfortableness.

### 4.2. Indexes of duration

As shown in Figure 7, several durations are defined. $t_1$ is the duration from changing of shuttle shift lever to beginning of clutch slipping, representing the delay of actuator and clutch clearance. $t_2$ is the clutch slipping time duration. $t_3$ is duration from end of clutch slipping to when 0 m/s is reached, representing the duration of torque converter running at reverse mode. $t_4$ is duration from the time of 0 m/s to when torque converter drives the vehicle back to initial position. $t_{\text{sum}}$ is the total duration, from the time of changing shuttle lever to when vehicle is back to initial position.

Test results of $t_1, t_2, t_3$ and $t_4$ of shuttle shift from forward to reverse are shown in Figure 8. Because the delay of actuator and clutch clearance is a fix behaviour of the transmission, it is not affected by test conditions, resulting to a constant $t_1$ value. At a given velocity, the first gear has a higher clutch speed, leading to longer slipping duration ($t_2$) than the second gear. The phenomena that the torque converter runs at reverse mode, where having a braking effect to vehicle, are observed at low velocities at first gear and at all test velocities at second gear. As velocity increases, the value of $t_3$ reduces. As the velocity increases, the $t_4$ decreases, which results from a joint effect of larger vehicle inertia and increased tractive torque.
The test results of $t_{\text{sum}}$ and $t_3+t_4$ are shown in Figure 9. Compared to first gear, the second gear has longer durations. Compared to empty load, the durations of full load increase.

At first gear, the $t_{\text{sum}}$ is about 2 s to 3 s. At second gear, the $t_{\text{sum}}$ is about 4 s to 5 s. For typical shoveling and loading operation, each work cycle is about 40 s, and it has four shuttle shifts. The total duration of shuttle shift takes an important part of work cycle duration and has direct influence to working efficiency of the wheel loader. So, $t_{\text{sum}}$ is chosen as an index of shuttle shift quality. $t_1$ is the index of delay of actuator and clutch clearance, and $t_2$ is the index of duration of clutch slipping. However, $t_1$ and $t_2$ are much smaller than $t_{\text{sum}}$, they are not suitable as indexes from vehicle perspective. As shown in Figure 9, the value of $t_3+t_4$ is more than 50% percent of $t_{\text{sum}}$, which means that torque converter plays a most important role in the duration of shuttle shift.
4.3. Index of dimension
As wheel loader usually works at areas with limited boundary, the dimension of shuttle shift also should be considered. As shown in Figure 7, overshoot distance is defined. Test result of overshoot distance is shown in Figure 10. Compared to first gear, the braking effect of clutch and torque converter is compromised by smaller gear ratio of second gear, leading to longer overshoot distance. Compared to empty load, the overshoot distance of full load is a little longer due to larger inertia. As velocity rises, the inertia increases, and overshoot distance becomes longer. Because the values of overshoot distance are able to reflect the effect of related factors, such as velocity, gear ratio and weight, it is considered as a reasonable index to represent the dimensional behaviour.

![Figure 10. Results of overshoot distance, shuttle shift from forward to reverse](image)

5. Conclusion
Objective assessment indexes of shuttle shift quality of wheel loader are investigated from aspects of comfortableness, duration and dimension in this study. The main findings are as follow.

The maximum acceleration, vibration dose value (VDV) and jerk of deceleration stage show a good linear correlation. The three indexes have similar representative ability for comfortableness assessment.

The total duration of shuttle shift is chosen as an index because it is directly related to working efficiency of wheel loader. The duration, in which torque converter plays a dominating role, is more than 50% of the total duration of shuttle shift, indicating that the duration of shuttle shift is mainly determined by torque converter’s characteristics.

The overshoot distance is considered as the index to represent the dimensional behaviour of the shuttle shift.

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