International Research Journal of Engineering and Technology (IRJET) e-ISSN: 2395-0056
Volume: 05 Issue: 07 | July-2018 www.irjet.net p-ISSN: 2395-0072

Design and Development of Forward Reverse Module for Tractor Transmission

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Abstract—*In certain agriculture applications like front loader, puddling the tractor require repeated forward and backward travel and frequent three point turns on field headlands during loading work. A tractor with limited speed range selection will affect the productivity of operation in reverse motion, as the operator will be stuck with limited speed selection. The forward- reverse capability and increased speed range can be optioned by a forward reverse module in transmission, which can provide on the go to and from motion by speed reversal. This forward reverse capability can be obtained by using a synchronizer system. Following paper highlights the development of synchronizer module, by studying different synchronizer placements in tractor model, so as to introduce forward-reverse shift capability. Also the factors like inertia, cone torque, coefficient of friction which affect synchronizer performance are studied in detail. Development of a synchronizer module will provide a large speed range selection such as same number of speeds in both forward and reverse, and improve work productivity.*

Key words— Synchronizer, Tractor transmission, Shift quality, shift time, synchronizer capacity, synchronizer durability test.

1. INTRODUCTION

In agriculture applications, the tractor plays an important role in carrying out land development activities in less time and with improved productivity. Tractor with front end loader applications require continuous change of shift from forward to reverse to maneuver to and fro constantly.

One of the tractor model is being used by customers for certain applications which lack the frequent forward/reverse gear change facility due to absence of F/R module. The current gearbox layout provides limited speed range selection to the customer and greatly affecting his work productivity and vehicle utilization. Development of such a separate forward-reverse module using synchronizer will provide a large speed range selection, with same number of speeds in both forward and reverse direction.

Fig 1. Tractor with front loader application

The layout and design of the synchronizer in transmission play an important role in driver's perception of shift quality of the vehicle. Vehicle manufacturer which develops the transmission knows what the end customer is looking for and what his expectations are. The Vehicle requirements in terms of shift quality are translated into specifications for shift impulse, shift time and detent force, Knob force and ease of gear shift.

Shift quality is an important criterion during the design phase of transmission. The specifications of shift quality are chalked out in the initial phase of layout development. Shift quality being an important characteristic is only noticeable by driver when is poor and unlike engine performance and handling it is rarely perceived. The shift quality can only be subjectively evaluated in the vehicle; as a result utmost importance is given to design of synchronizer, synchronizer placement and shift system design.

2. LITERATURE REVIEW

Single-cone clutch synchronizers were introduced on passenger car transmissions in the 1930s. However, the first paper to consider in detail the operation of these devices and to derive theoretical performance equations was published by M'Ewen in 1948 following his work on tank gearboxes during World War 11. This paper has been used as the basis for initial design calculations by transmissions engineers ever since and is still regarded as the definitive work on the subject. In the intervening years since publication of M'Ewen's paper, a number of studies have been conducted to define more clearly the factors affecting synchronizer design and operation.

Richard J. Socin & L. Kirk Walters [2] in their paper presented the design parameters for strut and cone type of synchronizer, including formulas, present design practices, methods of evaluation, and variables that most affect synchronizer performance.

I. Rosen, S. Kruk, P. O. Eker, H. Mellgren [3] presented design characteristics of different synchronizers with comparisons of designs, performance, and dependability in operation. The theory of operation is dealt with in detail. The influence of experience in practice on design from the effects of clash, hard gear changing, wear, clutch and oil drag are included. Suitable materials, machinery processes, and interdependence of dimensions are described. The paper concludes with notes on practical and laboratory tests and future development.

Syed T. Razzacki [4] presented method for designing a synchronizer in a transmission which has a plurality of components each defined by one or more parameters is provided. The method includes selecting a first parameter having a relationship to the transmission. A second parameter is selected based off of a relationship to the first parameter. Then, the synchronizer components are designed while simulating a synchronization episode using the first and second parameters.

Syed T. Razzacki, Jonathan E. Hottenstein [5] studied factors affecting shift quality. Although shift quality is not directly affected by the synchronizers, smooth and quick transition of gears, including up shift, downshift, and skip shift is logically a significant factor in accomplishing the fuel economy objective. The relationship parameters for smooth gear transition is mathematically established and experimentally verified. Synchronization torque measurement procedure is known, but index torque is usually not measured. For verification purposes a measurement method was formulated and a fixture was built accordingly.

David Kelly & Christopher Kent [6] created a dynamic model of the entire synchronizer selector mechanism, driveline and transmission has been created. The model predicts the gearshift quality for a given set of input parameters, which can be correlated against test data. The model can then be used for parameter studies to investigate potential improvements to gearshift quality. The model can also be used at the concept stage to indicate suitable specification for synchronizer geometry, component stiffness, mass and inertia.

Yuvraj V. Dhanal & Yuvaraj M. Jadhav [7] studied the effects of various factors like reflected inertia, drag torque, differential speed, synchronizing time, and gear shifting force on synchronizer capacity and developed test rig to carry out the test which will give the same test results as of traditional test rig.

Bhagyesh Chavan & S UdayaKumar [8] developed a synchronizer test rig to replicate field validation of tractor to lab validation and also accurately validate synchronizer life in transmission.

Hoshino.H [9] developed a simulation technique synchronization mechanism of a transmission gearbox installed in a heavy-duty truck. For shifting up from one gear to the other gear, the movement and contact force of the synchronizer components are simulated with an analytical model using ADAMS.

3. THEORY AND MATH

The function of a synchronizer is to provide a friction clutch inside the transmission that is activated when the vehicle operator makes a gear change. The working of synchronizer reduces to zero the relative speeds of the transmission gears, engine clutch disc systems and the output shaft during the shift period.

Almost all type of friction clutches has been used for synchronizers. Described below are the most popular type of synchronizers.

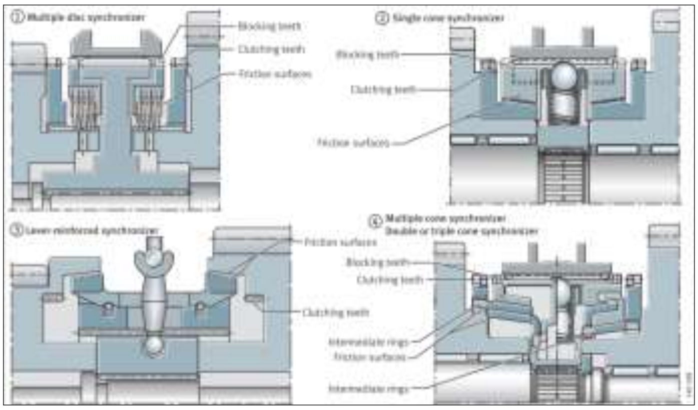


Fig.2 Different types of synchronizers (Ref: INA selector hub assembly, Product technical manual, Schaeffler Group)

This paper mostly deals with the cone type synchronizers because of their high torque capacity for relatively small size.

3.1 Basics of Synchronization

The components involved in synchronization process are shown in fig. 3 which are speed gears (1) , gear cones(2), synchronizer blocker ring (3), selector hub (4), spring (5), ball (6), strut (7) and shifter sleeve (8). The synchronization process can be divided into followings stages as below.

a. Shifter sleeve (8) moves from neutral position to detent position of strut (7).

b. The strut (7) detent load starts to build up due to spring

(5) and ball action (6).

c. Strut (7) pushes the synchronizer blocker ring (3) to the index position.

d. shifter sleeve (8) teeth chamfers contact blocker ring (3) teeth chamfers causing built up of friction between ring (3) and gear cone(2).

e. synchronizer ring (3) rotates slightly allowing the shifter sleeve (8) to pass through the cone (2).

f. Gear cone (2) rotates slightly allowing the shifter sleeve (8) to pass through and completing the synchronization process and ensuring positive locking.

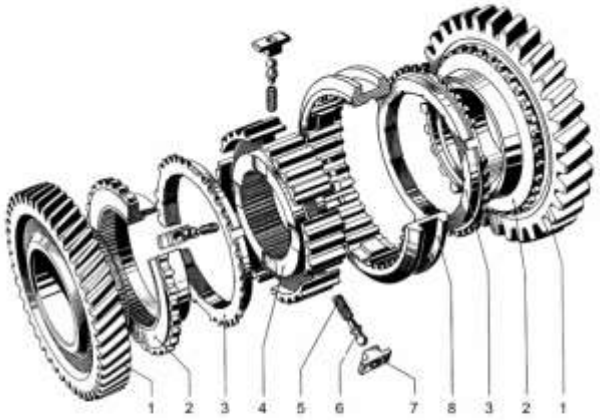


Fig 3. Single cone synchronizer- main components (Ref: INA selector hub assembly, Automotive Transmissions)

3.2 Performance parameters for Assessment

Gear shifting in manual transmission is function of four factors i.e. Synchronization time ,shift force, shifting mechanism leverage and shift travel which are further classified or dependent on the variables like cone torque, coefficient of friction, cone angle, index angle ,frictional area, gauge radius, drag torque etc. Also, the gear shift lever and shift system linkage establish a direct connection between the driver and the vehicle. The demands on comfort of gear shift are highest in such situations. The shift force should be as low as possible for all operating conditions and the shift time required should be as quick as possible.

In this paper, major parameters considered for initial assessment are described below. All the gear box specifications are initially defined and the shift times for different gearbox layouts are calculated. (Ref- Automotive Transmissions - Fundamentals, Selection, Design and Applications by Gisbert Lechner, Harald Naunheimer)

Synchronization time = $t_s = \frac{(W_2-W_1)I_R}{T_{C(avg)}}$ sec

W_2-W_1 = Speed difference between two synchronized gears

Synchronization time is the most important design consideration and is a function of how effectively the cone torques is developed, the maximum speed change of the component and the drag torque.

I_R = Reflected inertia of gear train to synchronizer being calculated.

$I_R = I_n * R^2_G$

I_n=Inertia

R^2_G = Gear ratio = $\frac{\text{Number of driving gear teeth}}{\text{number of driven gear teeth}}$

T_C= Cone torque = $\frac{Fa * \mu_k * R_k}{\sin\alpha_k}$ N-mm

Where,

F_a = Axial sleeve force exerted on synchronizer ring parallel to axis.

μ_k= Dynamic coefficient of friction between ring and cone.

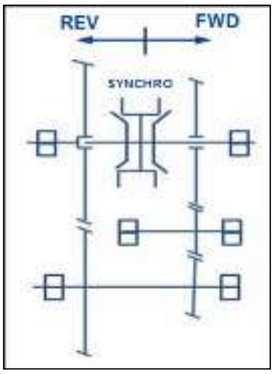
R_k= Mean cone radius.

α_k= cone angle of synchronizer.

4. DESIGN AND DEVELOPMENT PHASE

4.1 Tractor gearbox Scenario

Forward-Reverse module is an additional subsystem in gearbox, consisting of gears, shafts and synchronizer arrangement, which gives forward and reverse speeds with to and fro motion of lever. A stick diagram of forward –reverse module is shown below.



Currently, one of the current production tractor model is considered for Forward-Reverse module development. In loader applications easy forward-reverse movement of tractor is expected for ease of operations.

The base layout of tractor is shown in fig 4.which lacks the Forward-reverse capability.

Fig 4. Base layout for a tractor

For initial assessment three different concepts were studied for synchronizer module placement as follows:

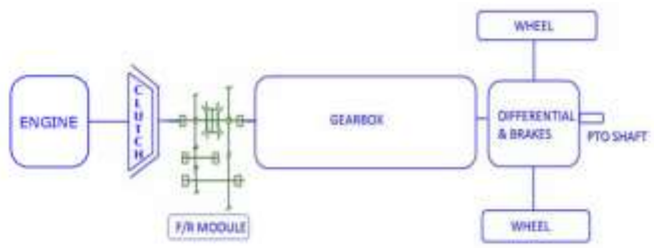


Fig 5. Concept 1

Fig.5 represents the concept 1 for tractor with forward-reverse module in which synchronizer is placed on clutch input driving shaft before the gearbox.

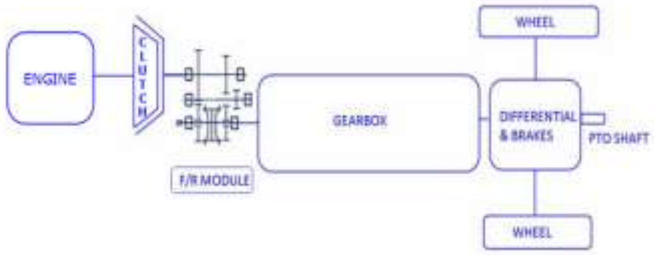


Fig 6. Concept 2

Fig.6 shows the concept 2 for tractor with forward-reverse module where synchronizer is placed on input driven shaft before the gearbox.

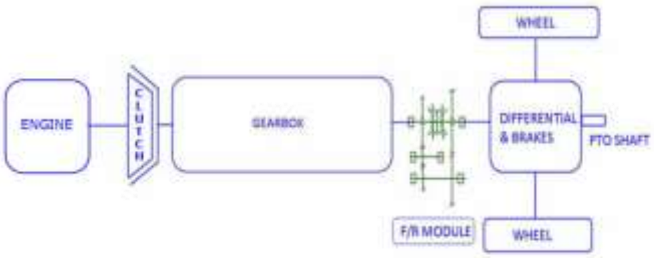


Fig 7. Concept 3

Fig.7 shows the concept 3 for tractor with forward-reverse module after the gearbox. The synchronizer performance was studied for the all three concepts and the layout with optimum performance was selected for further development.

5. EXPERIMENTAL STUDY AND RESULTS

5.1 Transmission Model

The tractor gearbox model was constructed in Romax designer software in which the "Synchronizer and clutch sizing module" was used. All subsequent analyses were performed using this software.

The Romax designer model is fully detailed static and dynamic model of gearbox and includes shafts, gears, bearings, synchronizer, differential and housing. The results were plotted based on the output from the dynamic analysis.

5.2 Analysis Method

The synchronizer performance calculations are divided into following sections.

1. Reflected Inertia calculation

The inertia reflected at the synchronizer due to the clutch plate, gears and shafts was calculated. The following data was required as input for reflected inertia calculations.

- Number of teeth for both driver and driven.
- Inertia of components.
- Clutch Plate Inertia

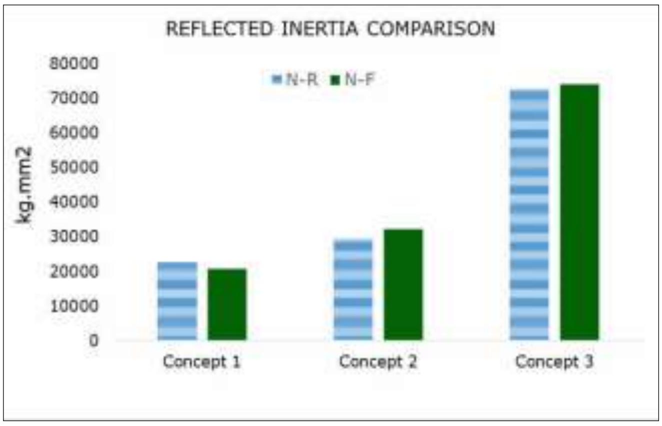


Fig 8. Inertia comparison for Forward Reverse shift

Fig.8 shows the comparison for inertia reflected at synchronizer for forward-reverse shifts for the three concepts. Initial observations show that for concept-1 the inertia reflected at synchronizer is less as compared to the other layouts. This is because, here only the clutch plate and input shaft inertia needs to be synchronized. In concept-2 the inertia values are slightly higher than concept-1 as the forward and reverse gears inertia comes into play. Whereas in concept-3 the inertia values are extremely high as here in upstream all the rotating speed gears inertia are considered.

2. Synchronization time (Shift time)

The synchronizer calculations are carried out at two different hand knob force of 130N being the lowest and 230N for maximum allowable force for fore-apt lever as per IS 10703.

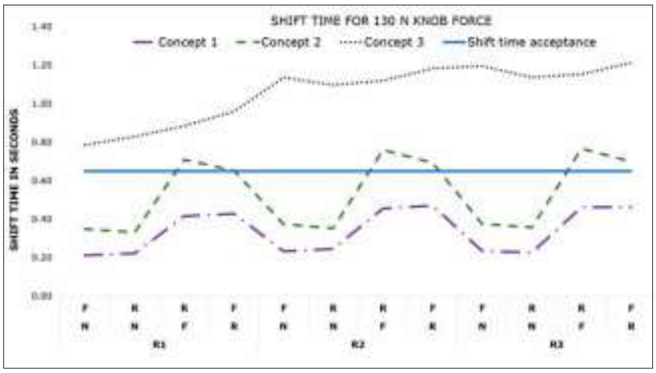


Fig 9. Shift time calculations for 130N knob force

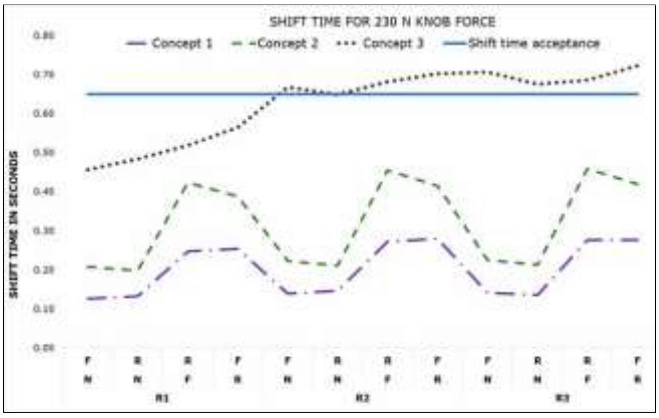


Fig 10. Shift time calculations for 230N knob force

Fig.9 and fig.10 shows the result for synchronization (shift time) for 130N and 230N hand lever force for all the three concepts. It can be observed that for concept 1, the shift time is within the acceptable limits for both the cases of knob force.

From above results it is clear that for concept 1 in which the synchronizer is placed on clutch input shaft before the gearbox, the inertia reflected on synchronizer is less, which results in lesser shift times. So for further detailed development, concept 1 was selected.

3. Selection of friction material for Synchronizer.

The most important factor for synchronization is cone torque. Cone torque is directly dependent on the variable, dynamic coefficient of friction. The remaining factors which determine cone torque (axial force from sleeve, cone angle and radius) can be considered fixed for a given design.

There are many different friction materials available in market for synchronizers; however we will focus on most common and popular friction surface combinations: steel friction cone/uncoated special brass synchronizer ring, steel friction cone/steel synchronizer ring with molybdenum friction coating and steel friction cone/steel synchronizer ring with a sprinkle sinter friction coating and carbon lined friction coating. Below table provides the frictional values for the mentioned materials.

Friction Surface Combination	Reference values
Steel	Coefficient of Friction μ
/special brass	0.08-0.11
/molybdenum	0.08-0.12
/sprinkle sinter	0.09-0.12
/carbon lined	0.1-0.14

(Ref: Automotive Transmissions Page no 329 and www.hoerbiger.com/Friction Systems)

Based on above values of coefficient of friction, the cone torque values were calculated for the synchronizer for concept 1 shown in fig.11.

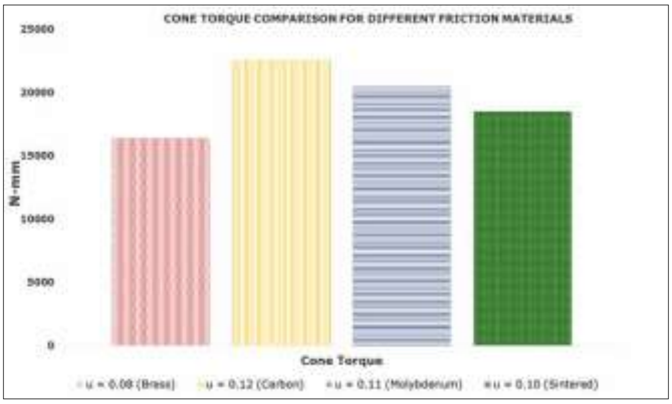


Fig.11 Cone torque comparison for friction materials

Also the shift time analysis was done for the different friction materials for the selection of synchronizer material for concept- 1 which is shown in fig.12

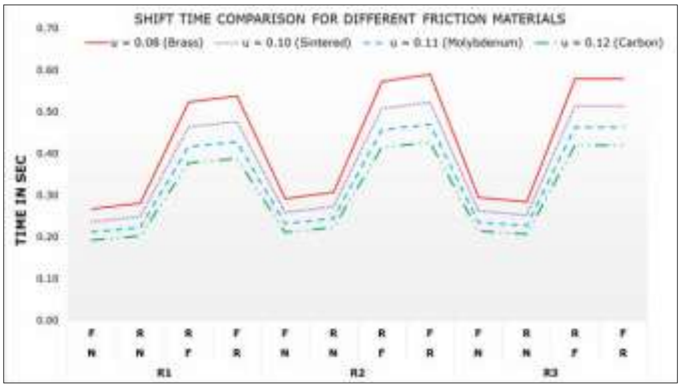


Fig.12 Shift time comparison for concept 1 with different friction materials

It can be seen from above comparison for cone torque and shift time of synchronizer with different friction materials, carbon lined friction material generates higher cone torque due to higher coefficient of friction value and leading to lesser shift time which is the major factor in selection of synchronizer for current tractor with loader application.

From this section one can understand that, for efficient performance and reliability of synchronizers following factors/parameters play a vital role:

a. Reduced inertia at input shaft+clutch disc inertia

b. Differentials speeds to be synchronized

c. Gear shifting force which may vary operator to operator

d. Synchronization time (shift time)

e. Cone torque and friction material

6. VALIDATION PHASE

6.1 Synchronizer Test rig setup

Tractor being widely used in variety of applications such as agriculture, construction, transport, certain field application like puddling and front end loader, subjects the tractor to severe transmission loading. Therefore robust design and high factor of safety is required for accomplishing customer needs.

Validating the synchronizer in lab is generally done on synchronizer test rig. On a synchronizer test ring, to simulate actual loads to the synchronizer, main clutch is attached to the drive shaft to simulate the actual working condition of tractor.

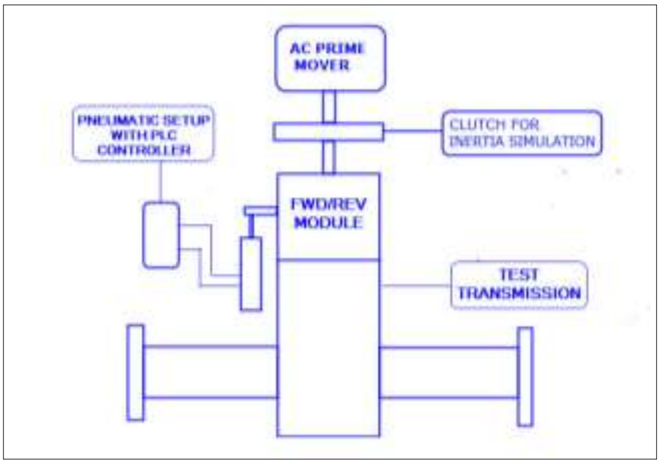


Fig.13 schematic diagram of synchronizer test rig

Fig.13 represents synchronizer test rig schematic diagram. The test rig is setup on a rigid base structure. A prime mover of suitable capacity is selected to drive the dummy transmission assembly. Pneumatic actuators and load cells are assembled in a rigid mounting fixture for shifting the gears. External lubrication circuit with adequate flow rate is connected in the transmission to provide the lubrication as per tractor level configuration during the synchronizer application. The entire setup is controlled by a simple programmable logical controller.

The gear shifting cycles are performed in desired gear shifts with intended shift force. The schedule or time interval for forward reverse shift is decided based on the experience and usage data of tractor for particular applications. The forward reverse gear shifts for durability cycle of synchronizer may range from 40k to 120k depending on the AAU (Average Annual usage) of the tractor and service life.

For synchronizer, the wear on friction surfaces is usually the factor that determines the service life. The permissible wearon synchronizer friction surfaces for given shift cycles should be within acceptable limit. The wear reserve on synchronizer unit is calculated by subtracting the operating clearance from the permissible wear.

The developed prototype transmission with forward reverse module was tested in lab on synchronizer durability test rig for some standard number of cycles calculated on the basis of the actual tractor usage in field. The wear pattern on the friction material was monitored at regular intervals during the test for life validation, as deterioration of friction lining wear beyond some limit cannot be tolerated.

Fig.14 Synchronizer wear gap characteristics during durability test

The synchronizer durability test was successfully completed with below observations;

1. Max wear on forward side and on reverse side was within the acceptable limit
2. Synchronization time till end did not cross the acceptance criteria.
3. No debonding of friction material from the cone surfaces.

7. SUMMARY/CONCLUSIONS

In this paper, we have tried to show, how synchronizer placement affects the gear shift time in a vehicle. By placing the synchronizer near to the clutch before speed box, the upstream reflected inertia on synchronizer is minimum, and the shift times achieved are within the desired acceptance limits. Also friction material has significant effect on performance and shift time of synchronizer. Higher coefficient of friction values results in higher cone torque values which ultimately helps in reducing the synchronizer time. However care must be taken to have proper lubrication to synchronizer system to have proper dissipation of heat generated due to friction. It is observed that lower shift times for lower force values are always acceptable as they tend reduce driver fatigue during field operations and improves the perception of the vehicle.

It is possible to analyze the effects of the different design parameters which affect the shift quality and subsequent action can be taken to reduce or improve their effect on synchronization time.

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