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1 Basic ideas for VECTO's new Transmission Control Unit

Here the basic ideas for the new Transmission Control Unit (TCU) are described.
The TCU does a continuous rating of every gear after a hypothetical gearshift (post-shift) for:

- Fuel consumption (FC), taking into account the combined efficiencies of engine and gearbox.
- Torque demand at the cardan shaft[1], and the available torque.
- Engine speed.

If another gear than the current one gets a better rating, and if shifting is possible, it is shifted to the better gear. To get the ratings for all gears, the hypothetical operating points post-shift for cardan shaft and engine in terms of rotational speed, rotational acceleration and torque are calculated every timestep.

2 Calculation flow in the Simulink model

Here the main calculation steps and assumptions are described. Additional info can be found in the `% Comments` in the Matlab functions, which are embedded in the Simulink model. The referring names in the model *are printed italic.*

The main steps, conducted during every timestep of the simulation. for the case "propulsion", i. e. cardan torque above 0 Nm, are:

Simulink block *Demand at cardan shaft and at gearbox input*

Determine the estimated vehicle velocity at the end of a hypothetical gearshift, after the phase of traction interruption. The road gradient is assumed to keep its current value during gearshift, so for the gradient the TCU does not "look ahead", but does "look down".

Lookup *Predicted vehicle velocity after gearshift*

Look into the hypothetical gearshift interval from middle to end, dependent on the expected relative velocity drop (higher drop → look closer to the end of the interval).

Lookup *Dt_pred / Dt_shift look-up*

Determine the predicted vehicle velocity in the hypothetical gearshift interval, somewhere in its second half.

*(v_veh_post_shift - v_veh_sum_curr) * (Dt_pred/Dt_shift) + v_veh_sim_current*.

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[1] The cardan shaft, also called "prop shaft", is the shaft between gearbox output and axle gear input.

In case "drive-off" the velocity for the gear selection is set to the maximum of (10 km/h) and (the velocity in the first gear at the lowest engine speed, where 99 % of the max. engine torque are reached).

drive_off, StartupVelocity

Determine <u>two</u> values for the vehicle acceleration: The current acceleration from the driver model, with the lower limit 0 m/s², and the acceleration reserve, which depends on the difference between demanded and simulated velocity.

In case of target velocity cycles the acceleration reserve depends on the difference from demanded to simulated velocity. If the simulated velocity is very close or at the target velocity, a slightly negative acceleration reserve is chosen (here -0.1 m/s²), to avoid too early downshifts. If the simulated velocity is further below the target velocity, here 10 km/h difference, the acceleration reserve is positive (here +0.2 m/s²), to select gears where a higher torque at the cardan shaft becomes available. Between (target velocity) and (target velocity minus velocity-difference) the acceleration reserve is linearly interpolated.

In case of measured, time-based velocity cycles the acceleration reserve at demanded velocity is set to 0 m/s², because the model shall not deviate from the demanded, measured velocity.

In case "drive-off" a predefined acceleration value is chosen, here 0.5 m/s².

Driver acceleration, a_rsrv_Dv_targ_curr_high, a_rsrv_Dv_targ_curr_low, StartupAcc

Calculate the predicted operation point of the cardan shaft in terms of torque and rotational speed for the different acceleration values:

One time with the driver acceleration, and one time with the acceleration reserve. In case "drive-off" only the one predefined acceleration value is chosen for both inputs (here +0.5 m/s²).

The two cardan torques are calculated backwards from the wheel forces: Gradient force (equal for both cases), acceleration force (from driver acceleration <u>or</u> from acceleration reserve), tyre rolling resistance (equal for both cases) and air drag (equal for both cases).

The result are two operating points of the cardan shaft, for the driver acceleration <u>or</u> for the acceleration reserve: Rot. cardan speed; rot. cardan acceleration; cardan torques; cardan power.

Backward vehicle dynamics, demanded accel., for FC-rating

Backward vehicle dynamics, demanded accel., for Tq-rating

Simulink block *Gear rating preprocessing* and Matlab function *GearRating*

Calculate for every gear the predicted engine operation point, for the cases driver acceleration and acceleration reserve, each case with the predicted values for gearbox losses, auxiliary torque and engine inertia torque: Rot. engine speeds; torques in FC-map; FC, if in permitted operation range.

Rate the gears according to the results from the preprocessing.

Determine the individual rating factor for every gear:

a) If inside of acceptable operation range for speed and for torque, where the torque was calculated from the acceleration reserve:

Rating is: Ratio (FC) to (power cardan shaft), where both values were calculated from the driver acceleration[2].

=> Low range of rating factors.

Case a), inside accept. speed range, and below torque limit, sub-block of *Preprocessing*

b) If inside of acceptable operation range for speed, but torque from acceleration reserve above the limit from engine full load or from gearbox input:

Rating is: Distance from demanded to possible torque at cardan shaft, where both values were calculated from the acceleration reserve, plus medium penalty.

=> Medium range of rating factors.

Case b), inside accept. speed range, and above torque limit, sub-block of *Preprocessing*

c) If outside of acceptable operation range for speed:

Rating is: High penalty for inacceptable engine speed, increasing with distance to range of acceptable engine speed.

=> High range of rating factors.

Case c), outside accept. speed range, sub-block of *Preprocessing*

The ratings are calculated after the preprocessing in the Matlab function *GearRating.*

Remark to the calculation of the max. acceptable engine speed, case c):

In case "propulsion" the max. acceptable engine speed depends on the ratio of the (inertia force at wheel) to the (total force at wheel), called *share_F_inert*.

If this ratio is high, at low velocities and in low gears, then the HDV model accelerates quickly. So high engine speeds shall be avoided to enable early upshifts, and also to avoid over-revving. Thus the max. acceptable engine speed is set to (the max. engine speed, where 99 % of the max. engine torque are reached, called *w_eng_Tq99_high*).

If *share_F_inert* is low, then the share of gradient force plus road load at the wheel force is high, e. g. at uphill sections or high velocities. So the max. acceptable engine speed is set to (the max. engine speed, where the max. power is reached, called *w_eng_Pmax*), because late upshifts are necessary.

Between high and low shares of the inertia force at the wheels the max. acceptable engine speed is calculated from *w_eng_Tq99_high*, *w_eng_Pmax* and a characteristic curve, called *TCU_w_max_fact_accel.*

This decrease of the max. acceptable engine speed is reduced for high simulated velocities (curve *TCU_w_max_fact_vel*). This function was introduced to avoid too early upshifts during necessary accelerations at uphill sections on motorways, due to the lowered max. acceptable engine speed.

[2] The (power cardan shaft) per gear is limited by the engine full load power or by the max. permitted gearbox input torque, if the power demand from the driver acceleration would exceed those limits.

Matlab function *ShiftDecision*

Case " propulsion", i. e. positive power at cardan shaft.

Apply rules to avoid impossible shifts, gearhunting and the over-revving of the engine, and to enable exceptional shifts in case of too low or too high engine speed.

If a possible gear got a lower rating factor than the current gear, and shifting is permitted or necessary:

=> Gearshift to the most beneficial gear.

Case " coasting or braking", i. e. negative power at cardan shaft.

For the case "coasting or braking", i. e. cardan torque below 0 Nm, a simple speed-dependent gearshift control is applied.

More info can be found in the `% Comments` in the Matlab function *ShiftDecision*.

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3 Input data for proposed Transmission Control Unit

In this section the input data for the TCU are enlisted. The referring names in the Simulink model `Proposal_TCU_VECTO_2018_03_29_R2015a.slx` *are printed italic.*

3.1 Data from the rest of the vehicle model

These signals from the rest of the model in the current simulation timestep are used in the TCU:

- Simulation time (*Clock*)
- Simulated vehicle velocity (*Vehicle velocity [m/s]*)
- Demanded vehicle velocity (*Demanded velocity [m/s]*)
- Simulated vehicle position on the drive cycle (*Vehicle position [m]*)
- Ratio of (inertia force at wheels) to (sum of forces at wheels) (*share_F_inert*)
- Torque at the cardan shaft (*Current cardan torque [Nm]*)
- Number of engaged gear (*CurrentGearNumber*)
- Rotational engine speed (*Engine speed [rad/s]*)
- Required acceleration from the driver model (*Driver acceleration [m/s^2]*)
- Drive-off signal from the driver model (*drive_off*)

3.2 Vehicle data

The enlisted data is imported anyway by VECTO, and used in addition in the TCU.

- Gravitational constant (*Gravity_Constant*)
- Density of ambient air (*Density_Air_Ambient*)
- Lookup table of road gradient (*Road gradient look-up*), from standard drive cycle

- Overall test mass: Motor vehicle, plus body(s), plus trailer(s), plus payload (*m_tot*)
- Summarised rotational inertia of all wheels (*Wheel_Inertia*)
- Rolling resistance coefficients of tyres per axle (*Wheel_RRC*)
- Share of single axle loads at overall test mass (*sh_i*)
- Effective air drag area (*CdxA*), if so with crosswind correction

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o Dynamic rolling radius of wheels at powered axle(s) (*Wheel_Radius*)

o Gear ratio of axle gear (*Axlegear_GearRatio*)

o Loss map of axle gear, related to its output shaft (*Axle losses output*): Rot. speed axle output, torque axle output, axle torque loss referred to its output shaft

o Rotational inertia of axle gear, referred to its input shaft (*Axlegear_Inertia*)

o Rotational inertia of cardan shaft (*Cardanshaft_Inertia*)

o Gear ratio of retarder drive, n_{ret} / n_{card} (*Retarder_GearRatio*)

o Curve of retarder torque loss, referred to the retarder shaft (*Retarder torque loss [Nm]*)

o Rotational inertia of retarder (*Retarder_Inertia*)

o Gear numbers of gearbox gears (*Gearbox_GearNumber*), a vector with one entry per gear

o Gear ratios of gearbox gears (*Gearbox_GearRatio*), a vector with one entry per gear

o Loss maps gearbox gears, related to its output shaft (*Gearbox losses output*): Rot. speed gearbox output, torque gearbox output, gearbox torque loss referred to its output shaft. A matrix with one map per gear.

o Loss maps gearbox gears, related to its input shaft (*Gearbox losses input*): Rot. speed gearbox input, torque gearbox input, gearbox torque loss referred to its input shaft. A matrix with one map per gear.

o Rotational inertia of gearbox input, referred to its input shaft (*Gearbox_Inertia*)

o Torque limits of gearbox input (*Gearbox_MaxTorqueIn*), a vector with one entry per gear

o Average constant power demand of engine auxiliaries (*Engine_AuxPowerDraw*)

o Engine idle speed (*Engine_IdleSpeed*)

o Max. engine speed (*Engine_MaxSpeed*)

o Rotational inertia of engine plus flywheel (*Engine_Inertia*)

o Curve of max. engine torque (*Engine full load curve*)

o Fuel consumption map of engine (*Fuel consumption table*)

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3.3 Data specific for the Transmission Control Unit

=> See also the info in the `% Comments` of the script ...*\b_load_input_data\b100_input_TCU.m*.

- Map of predicted vehicle velocity after a gearshift, "post-shift" (*Predicted vehicle velocity after gearshift*). Calculated during the pre-processing. Example data is shown in Figure 1.

y-axis: current simulated road gradient; $grad_{sim,curr}$; [%]	**z-axis:** estimated vehicle velocity post-shift; $v_{veh,post\text{-}sh}$; [km/h]												
24	*0.0*	*1.8*	*11.8*	*21.7*	*31.7*	*41.7*	*51.7*	*61.6*	*71.6*	*81.6*	*91.5*	*101.5*	*111.4*
22	*0.0*	*2.4*	*12.4*	*22.4*	*32.4*	*42.3*	*52.3*	*62.3*	*72.2*	*82.2*	*92.1*	*102.1*	*112.0*
20	*0.0*	*3.1*	*13.0*	*23.0*	*33.0*	*43.0*	*52.9*	*62.9*	*72.9*	*82.8*	*92.8*	*102.7*	*112.7*
18	*0.0*	*3.7*	*13.7*	*23.7*	*33.7*	*43.6*	*53.6*	*63.6*	*73.5*	*83.5*	*93.4*	*103.4*	*113.3*
16	*0.0*	*4.4*	*14.4*	*24.3*	*34.3*	*44.3*	*54.3*	*64.2*	*74.2*	*84.1*	*94.1*	*104.1*	*114.0*
14	*0.0*	*5.0*	*15.0*	*25.0*	*35.0*	*45.0*	*54.9*	*64.9*	*74.9*	*84.8*	*94.8*	*104.7*	*114.7*
12	*0.7*	*5.7*	*15.7*	*25.7*	*35.7*	*45.6*	*55.6*	*65.6*	*75.5*	*85.5*	*95.4*	*105.4*	*115.3*
10	*1.4*	*6.4*	*16.4*	*26.4*	*36.3*	*46.3*	*56.3*	*66.2*	*76.2*	*86.2*	*96.1*	*106.1*	*116.0*
8	*2.1*	*7.1*	*17.1*	*27.0*	*37.0*	*47.0*	*57.0*	*66.9*	*76.9*	*86.8*	*96.8*	*106.7*	*116.7*
6	*2.8*	*7.7*	*17.7*	*27.7*	*37.7*	*47.7*	*57.6*	*67.6*	*77.6*	*87.5*	*97.5*	*107.4*	*117.4*
4	*3.4*	*8.4*	*18.4*	*28.4*	*38.4*	*48.4*	*58.3*	*68.3*	*78.3*	*88.2*	*98.2*	*108.1*	*118.1*
2	*4.1*	*9.1*	*19.1*	*29.1*	*39.1*	*49.0*	*59.0*	*69.0*	*78.9*	*88.9*	*98.9*	*108.8*	*118.7*
0	*4.8*	*9.8*	*19.8*	*29.8*	*39.8*	*49.7*	*59.7*	*69.7*	*79.6*	*89.6*	*99.5*	*109.5*	*119.4*
-2	*5.5*	*10.5*	*20.5*	*30.5*	*40.5*	*50.4*	*60.4*	*70.4*	*80.3*	*90.3*	*100.2*	*110.2*	*120.1*
-4	*6.2*	*11.2*	*21.2*	*31.2*	*41.1*	*51.1*	*61.1*	*71.0*	*81.0*	*91.0*	*100.9*	*110.9*	*120.8*
-6	*6.9*	*11.9*	*21.9*	*31.9*	*41.8*	*51.8*	*61.8*	*71.7*	*81.7*	*91.7*	*101.6*	*111.6*	*121.5*
-8	*7.6*	*12.6*	*22.6*	*32.5*	*42.5*	*52.5*	*62.5*	*72.4*	*82.4*	*92.3*	*102.3*	*112.2*	*122.2*
-10	*8.2*	*13.2*	*23.2*	*33.2*	*43.2*	*53.2*	*63.1*	*73.1*	*83.1*	*93.0*	*103.0*	*112.9*	*122.9*
-12	*8.9*	*13.9*	*23.9*	*33.9*	*43.9*	*53.8*	*63.8*	*73.8*	*83.7*	*93.7*	*103.7*	*113.6*	*123.5*
-14	*9.6*	*14.6*	*24.6*	*34.6*	*44.5*	*54.5*	*64.5*	*74.5*	*84.4*	*94.4*	*104.3*	*114.3*	*124.2*
-16	*10.3*	*15.3*	*25.3*	*35.2*	*45.2*	*55.2*	*65.2*	*75.1*	*85.1*	*95.0*	*105.0*	*114.9*	*124.9*
-18	*10.9*	*15.9*	*25.9*	*35.9*	*45.9*	*55.8*	*65.8*	*75.8*	*85.7*	*95.7*	*105.7*	*115.6*	*125.5*
-20	*11.6*	*16.6*	*26.6*	*36.6*	*46.5*	*56.5*	*66.5*	*76.4*	*86.4*	*96.4*	*106.3*	*116.3*	*126.2*
-22	*12.2*	*17.2*	*27.2*	*37.2*	*47.2*	*57.1*	*67.1*	*77.1*	*87.0*	*97.0*	*107.0*	*116.9*	*126.9*
-24	*12.9*	*17.9*	*27.9*	*37.8*	*47.8*	*57.8*	*67.8*	*77.7*	*87.7*	*97.6*	*107.6*	*117.5*	*127.5*
	5	**10**	**20**	**30**	**40**	**50**	**60**	**70**	**80**	**90**	**100**	**110**	**120**
	x-axis: current simulated vehicle velocity; $v_{veh,sim,curr}$; [km/h]												

Figure 1. Generic tractor-trailer model, test mass 34.6 t. Estimated vehicle velocity after a gearshift ("post-shift"), limited to 0 km/h[3]. Calculated for a traction interruption of 1 s, for AMT gearboxes

[3] During traction interruption in idle gear, these forces act on the coasting vehicle: Gradient force; rolling resistance of tyres; air drag (with crosswind correction); friction losses in idling axle gear and in idling secondary retarder.
The shown table was calculated with the resulting acceleration from the acting forces during 1 s coasting.
The nodes for $v_{veh,sim,curr}$ in Simulink are 5, 10, 20, ..., 160 km/h, and for $grad_{sim,curr}$ -24, -23, ..., +24 %.

○ Curve for the share of prediction duration at the gearshift duration (*Dt_pred / Dt_shift look-up*). Example data is shown in Figure 2.

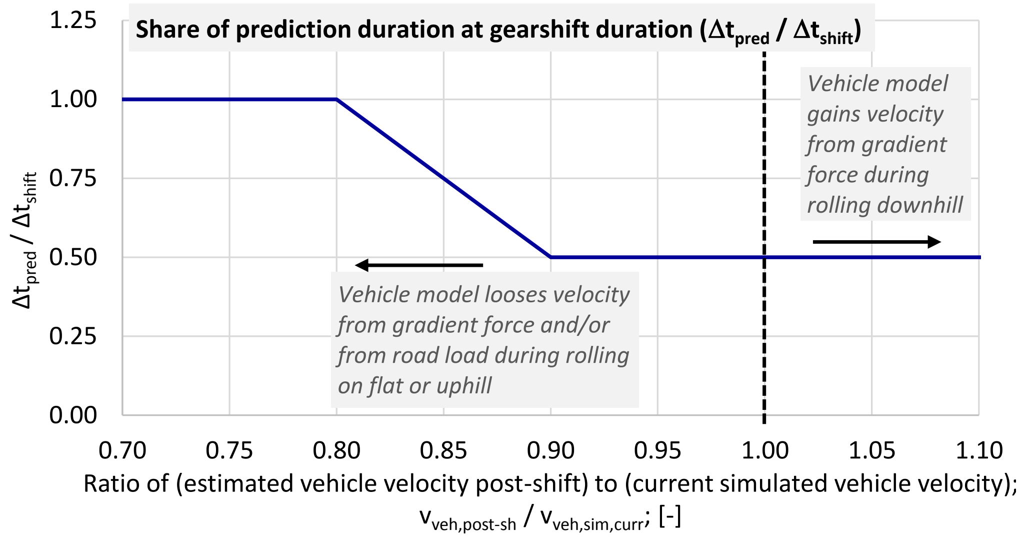


Figure 2. Dependence of the share of prediction duration at the gearshift duration (Δt_{pred} / Δt_{shift}) on the ratio of velocity post-shift to velocity current ($v_{veh,post-sh}$ / $v_{veh,sim,curr}$)

○ Curve for the acceleration reserve (x-axis: *v_veh_sim_curr*. y-axis: interpolated between *a_rsrv_Dv_targ_curr_low* and *a_rsrv_Dv_targ_curr_high*. The acceleration reserve for a low difference between demanded and simulated vehicle velocity was set to constant -0.1 m/s², and for differences above 10 km/h to +0.2 m/s². The max. velocity difference, here 10 km/h, is defined by the variable *Dv_targ_curr_range_kmh*.

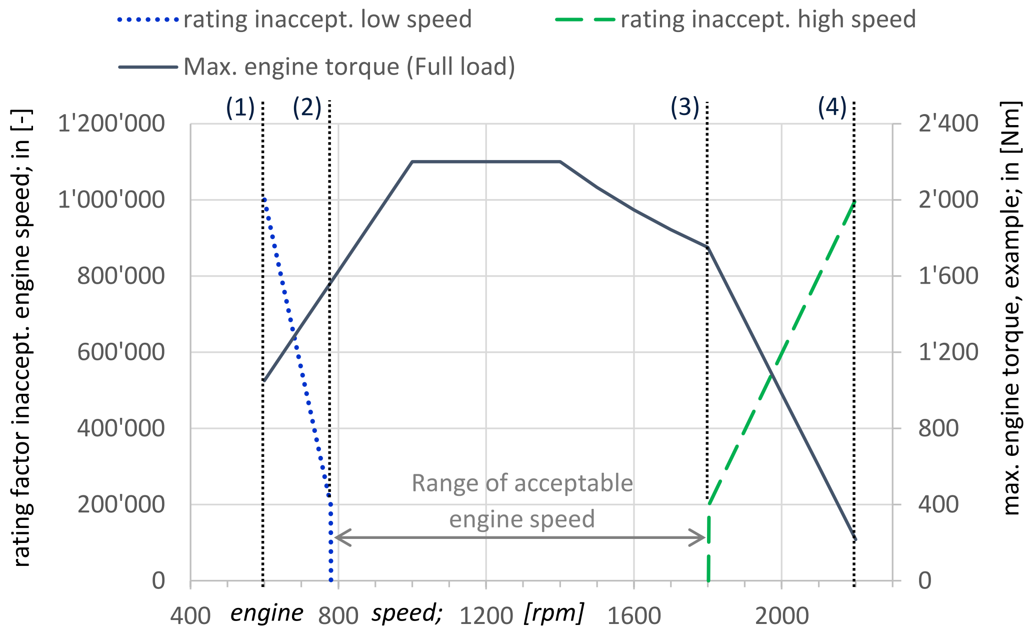
○ Curves for the calculation of the acceptable max. engine speed.
This function is described in the script *b100_input_TCU.m*, lines 55 to 91.

○ Medium penalty for gears which exceed a torque limit of engine full load or gearbox input, e. g. 100'000 = 1.0e5 (in function *GearRating*)

○ Low limit of acceptable engine speed (*w_eng_accept_low*), a vector with one entry per gear. E. g. at 15 % of the distance between idle speed and max. speed at max. power. Calculated from the curve of max. engine torque.

○ High limit of acceptable engine speed (*w_eng_accept_high*), a vector with one entry per gear. Calculated depending on the share of inertia force at the total wheel force.

○ High penalty for gears where the predicted engine speed is outside of the acceptable range. E. g. penalties of 200'000 = 2.0e5 and higher (in function *rating_inaccept_speed*). Example data is shown in Figure 3.



(1) idle speed of engine ($n_{eng,idle}$)

(2) x % of distance between (idle speed) and (speed at max. power), here set to 15 %.

(3) max. speed at max. power ($n_{eng,P\text{-}max}$)

(4) max. speed of engine ($n_{eng,max}$); ***or*** max. speed of gearbox input shaft ($n_{gb\text{-}in,max}$)

Figure 3. Definition of range of acceptable engine speeds; rating factors for inacceptable speeds. The max. acceptable engine speed (right green line) is decreased during high accelerations at low simulated velocities. Compare the description if the script *b100_input_TCU.m*, lines 55 to 91.

○ Duration of gearshift (*GearChangeTime*), equals the duration of the traction interruption.

○ Possible increase of gear number during one upshift (*AllowedGearRangeUp*), e. g. 2. That means from gear 3 the upshift is possible to the gears 4 or 5, but not to gear 6.

○ Possible decrease of gear number during one downshift (*AllowedGearRangeDown*), e. g. 3. That means from gear 12 the downshift is possible to the gears 11, 10, or 9, but not to gear 8.

○ Min. duration between shift and subsequent shift (*DelayShift*)

○ Min. duration between downshift and subsequent upshift (*DelayDownUp*)

○ Min. duration between upshift and subsequent downshift (*DelayUpDown*)