Trace Generation in EMSBench

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Abstract

This document describes the model that underlies the trace generator of EMSBench.

Contents

Table 1: Tyre labelling

195/70	R	14	86	H
w / r_t	-	d_r	-	-

1 Parameters

All parameters and associated units are depicted in table 3. Please note that we use rounds (revolution of the crank shaft) as unit for angular parameters to simplifie calculations.

1.1 Car Parameters

- Tyres with (see also tab. 1):
  - Width w [mm]
  - Aspect ratio r_t [%]
  - Rim diameter d_r ["]
- Transmission ratio of cardan shaft and/or axle r_a
- Transmission ratios of gears $\{G_1 \dots G_5\}$
- idle speed of engine $U_I[\mathrm{min}^{-1}]$
- derived idle speed of engine:

$$\omega_I = \frac{U_I}{60} \frac{\mathrm{min}}{\mathrm{s}} \tag{1}$$

Calculation of tyre circumference:

- Flank height h_f[mm] of tyre:

$$h_f = w \frac{r}{100} \tag{2}$$

- Wheel diameter d_w[mm]:

$$d_w = 2.54 \frac{\mathrm{mm}}{\mathrm{in}} d_r + 2h_f \tag{3}$$

- Tyre circumference C:

$$c_w = \pi d_w \tag{4}$$

1.2 Driving Cycle

phase:

- acceleration $a[\frac{m}{s^2}]$
- speed $v_s, v_e[\frac{km}{h}]$
- duration $d[s]$
- gear $g[0\dots5]$; gear 0 stands for any time the engine is idle, i.e. when the clutch is pressed and thus disconnects the wheels from the engine.

Basic calculations:

- acceleration $\dot{\omega}_w$ of wheel (if $a \neq 0$):

$$\dot{\omega}_w = \frac{a}{\frac{d_w}{1000}\frac{\mathrm{m}}{\mathrm{mm}}} \tag{5}$$

- acceleration $\dot{\omega}_c$ of crank shaft (if $a \neq 0$):

$$\dot{\omega}_c = \dot{\omega}_w G_g r_a \tag{6}$$

A simple example for a driving cycle is shown in table 2. Further examples can be found in appendix A.

Table 2: Example for driving cycle (excerpt from urban cycle, operations 6-13)

Op. Nr.	Operation	Acc.	Speed	Dur.	Gear
1	Idling	-	-	21	16 s PM + 5 s K1
2	Acceleration	0,83	0-15	5	1
3	Gear change	-	-	2	1→ 2
4	Acceleration	0,94	15-32	5	2
5	Steady speed	-	32	24	2
6	Deceleration	-0,75	32-10	8	2
7	Dec., clutch diseng.	-0,92	10-0	3	K2
8	Idling	-	-	21	16 s PM + 5 s K1

2 Model

2.1 Model Assumptions

- Ideal driver and engine: engine speed adapts exactly according to driving cycle
- no car speed is lost while clutch is disengaged for gear change

Table 3: Parameters used in trace generation

Symbol		Domain	Unit	Description
Car				
w	:	$\mathbb{R}^+$	mm	Tyre width
r_t	:	$[1 \ldots 100]$	%	Aspect ratio flank/width
d_r	:	$\mathbb{R}^+$	in	Rim diameter
r_a	:	$\mathbb{R}^+$	-	Transmission ratio of cardan shaft and/or axle (input/output)
$g_{1 \ldots 5}$	:	$\mathbb{R}^+$	-	Transmission ratio of gears 1 to 5 (input/output)
U_I	:	$\mathbb{R}^+$	min^{-1}	Idle speed of engine
α_I	:	$\mathbb{R}^+$	s^{-2}	Absolute value of angular acceleration to reach idle speed when engine idle
ω_I	:	$\mathbb{R}^+$	s^{-1}	Idle speed of engine (eq. (1))
h_f	:	$\mathbb{R}^+$	mm	Flank height of tyre (eq. (2))
d_w	:	$\mathbb{R}^+$	mm	Wheel diameter (eq. (3))
c_w	:	$\mathbb{R}^+$	mm	Tyre circumference (eq. (4))
Rotary Sensor				
n_P	:	$\mathbb{N}$	-	Number of primary teeth on rotary sensor
n_S	:	$\mathbb{N}$	-	Number of secondary teeth on rotary sensor
O_P	:	$\{\text{abs}, \text{pres}\}$	-	Primary signal
O_S	:	$\{\text{abs}, \text{pres}\}$	-	Secondary signal
Δ_P	:	$\mathbb{R}^+$	(rounds)	Angular distance between two adjacent primary teeth
Δ_S	:	$\mathbb{R}^+$	(rounds)	Angular distance between two adjacent secondary teeth
ϕ_S	:	$[3\Delta_P, 4\Delta_P)$	(rounds)	Angular distance between first primary and first secondary tooth; see 3.3.3 for details
Driving Cycle				
a	:	$\mathbb{R}$	ms^{-2}	Acceleration
v_s	:	$\mathbb{R}^+$	kmh^{-1}	Car speed at start of operation
v_e	:	$\mathbb{R}^+$	kmh^{-1}	Car speed at end of operation
d	:	$\mathbb{R}^+$	s	Duration of operation
g	:	$[0 \ldots 5]$	-	Gear used in operation (0 = clutch disengaged)
α_w	:	$\mathbb{R}$	s^{-2}	Angular acceleration of wheel
Crank Shaft Motion				
$\varphi(t)$	:	$\mathbb{R}_0^+$	(rounds)	Angular position of crank shaft
$\omega(t)$	:	$\mathbb{R}^+$	s^{-1}	Angular velocity of crank shaft
α	:	$\mathbb{R}$	s^{-2}	Angular acceleration of crank shaft

Input: $\varphi(t) \in \mathbb{R}^+$
Output: $O_P \in \{\text{absent}, \text{present}\}$
$O_S \in \{\text{absent}, \text{present}\}$

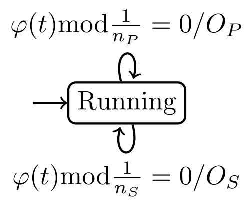

Figure 1: Rotary Sensor

- FreeEMS NipponDenso uses 24/2 sensor at cam shaft which has half the speed of the crank shaft. Simplify model by assuming 12/1 sensor mounted to crank shaft, amounts to same behaviour
- engine yields constant acceleration if accelerated/decelerated

2.2 Rotary Sensor

Figure 1 depicts the behaviour of the rotary sensor. The automaton uses the current angular speed $\varphi(t)$ of the crank shaft as input. Any time a primary or secondary tooth passes a sensor, a corresponding signal O_p or O_S is emitted.

2.3 Crank Shaft

The behaviour of the crank shaft is depicted in figure 2. The model develops the angular position $\varphi(t)$ and the angular velocity $\omega(t)$. Speed changes are managed through the angular acceleration α which can be changed through the α_N input. If a new α is set, the currently developed position and speed are saved as new initial values, and the current time is stored as new time offset. Setting of α must ensure that the angular velocity $\omega(t)$ never drops below 0 (not contained in the model).

2.4 Determination of α

Only under certain circumstances, accelerations a of the car from a driving cycle can be translated directly into angular accelerations of the crank shaft. There are a number of special situations, that also require some more work. Basically, we can describe the behaviour of the crank shaft as consisting of phases with constant angular acceleration. Each phase is a tuple (α, d) where α is the acceleration of this phase, and d is its duration.

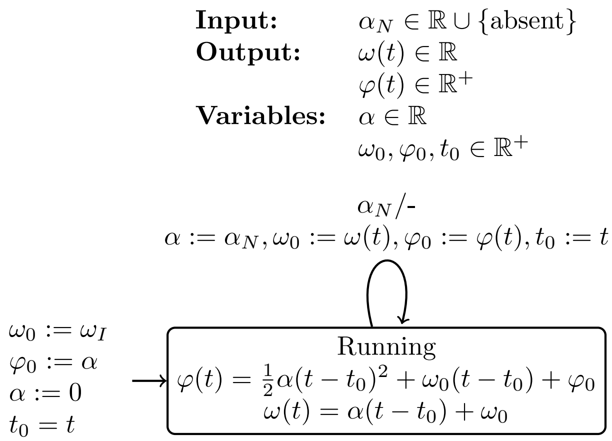

Figure 2: Crank shaft behaviour

2.4.1 Regular Operation

A regular operation is on hand, if (1) the acceleration during an operation is constant, and (2) there is no gear change during the operation. These condition is fulfilled by the following operations of a driving cycle: *idling*, *steady speed*, *deceleration*. Additionally, if an *acceleration* operation has a start speed $\neq 0$, it is also considered as a regular operation.

Idling

$$\alpha = \alpha_I \tag{7}$$

Steady Speed

$$\alpha = 0 \tag{8}$$

Acceleration and Deceleration

$$\alpha = r_a g_i \frac{a}{c_w} \frac{1000\text{mm}}{\text{m}} \tag{9}$$

2.4.2 Driveaway from Standstill

Actual behaviour: Driver slowly releases clutch, may press accelerator pedal.

Modeling: Simplify! Assume engine speed is constant (idle speed) until clutch closed, then increases according to acceleration. Use acceleration to calculate time until clutch closed (where engine idle speed matches car speed).

relationship car speed $\leftrightarrow$ engine speed:

$$\omega(t) = r_a g_i \frac{v(t)}{\frac{c_w}{1000} \frac{\text{m}}{\text{mm}}} \tag{10}$$

with

$$v(t) = at + v_0 \tag{11}$$

Now we need to find the time t_I with $\omega(t_I) = \omega_I$.
Thus solve for t:

$$r_a g_i \frac{at_I + v_0}{\frac{c_w}{1000} \frac{m}{mm}} = \omega_I \tag{12}$$

with $v_0 = 0$ due to standstill, we get:

$$t_I = \frac{\omega_I}{r_a g_i a} \frac{c_w}{1000} \frac{m}{mm} \tag{13}$$

Thus, we have a first phase of duration t_I according to eq. 13 where $\alpha = 0$ and $\omega(t) = \omega_I$. In in the second phase, α is calculated according to eq. 9.

2.4.3 Gear Change

Actual behaviour: driver presses clutch and releases accelarator pedal, changes gear, releases clutch and presses accelerator.

Modeling: Split gear change operation in two phases with equal duration. Let d_g be the total duration of the gear change operation. Then each phase has a duration of $\frac{d_g}{2}$.

1. **Disengagement of clutch:** Assume that clutch and accelerator pedal are disengaged instantly at the beginning of this phase. Then, ω changes with α_I until ω_I reached or end of phase is reached. Depending on the initial angular velocity ω_0, the angular acceleration must be chosen as:

$$\alpha_g = \begin{cases} -\alpha_I & : \omega_0 > \omega_I \\ 0 & : \omega_0 = \omega_I \\ \alpha_I & : \omega_0 < \omega_I \end{cases} \tag{14}$$

   Angular velocity develops as:

$$\omega(t) = \omega_0 + \alpha_g t \tag{15}$$

   Assume that phase starts at $t = 0$. Distinguish <u>two</u> cases:

   (a) If there exists a $t_I < \frac{d_g}{2}$ such that $\omega(t_I) = \omega_I$, introduce two phases (α_g, t_I), $(0, \frac{d_g}{2} - t_I)$.

   (b) If no such t_I exists, introduce <u>one</u> phase $(\alpha, \frac{d_g}{2})$.

2. **Engagement of clutch with new gear:** Assume that the gear is changed at the beginning of this phase, and the clutch is finally closed exactly at the end of this phase. The aim is to develop $\omega(t)$ in such a manner that $\omega(d_g)$ matches the new rotation speed at the end of the phase. To simplify calculations, we renormalise the time base to $t = 0$ at the beginning of the phase, and let ω_0 be the angular velocity at the

end of the previous phase. Let v be the current speed of the car (v_e of previous and v_s of next phase). Then, the target angular speed $\omega(\frac{d_g}{2})$ is

$$\omega(\frac{d_g}{2}) = r_a g_i \frac{v}{\frac{c_w}{1000}\frac{\mathrm{m}}{\mathrm{mm}}} \tag{16}$$

Then, α_G is calculated as

$$\alpha_G = \frac{2}{d_g}\left(\omega(\frac{d_g}{2}) - \omega_0\right) = \frac{2}{d_g}\left(r_a g_i \frac{v}{\frac{c_w}{1000}\frac{\mathrm{m}}{\mathrm{mm}}} - \omega_0\right) \tag{17}$$

Further assume that no speed is lost while clutch is disengaged.

2.4.4 Deceleration with Clutch Disengaged

When the car is decelerated with the clutch being disengaged, the engine speed should approximate ω_I. Let d_d be the total duration of this operation. We model this operation with two phases:

1. **Approximation:** If $\omega(t) = \omega_I$, this phase is skipped. Else, the engine speed has to drop or rise to ω_I. Therefore, α_d is chosen according to eq. 14. Again, assume that this phase starts at $t = 0$. Then, the phase ends at t_a with:

$$\omega(t_a) = \omega_I \tag{18}$$

   Combine with eq. 15 and solve for t_a and add phase $(\alpha_d, \min(t_a, d_d))$.

2. **Idling:** If $t_a \geq d_d$, this phase is skipped. Else, the engine speed stays constant. We add a phase $(0, d_d - t_a)$.

3 Trace Generation

3.1 Preliminary Considerations

Actual generation of traces on embedded platform should be as simple as possible. If enough memory is available, it would be possible to calculate all signal times offline, such that the actual generator program simply runs through a table. Due to the vast memory requirements of such an approach, we utilise a hybrid approach instead. At least parts of the necessary calculations are performed offline. Our aim is to implement trace generation through a composition of the automatons described in sections 2.2 and 2.3. Input data for these models is provided in pairs (t_N, α_N), where t_N is the time when the angular acceleration changes to α_N.

3.2 Preprocessor

The preprocessor transforms a driving cycle table (for examples, see appendix A) into an angular acceleration table for the actual trace generator. Thereby, the preprocessor proceeds as described in section 2.4.

Table 4: Parameters for primary teeth calculations

Δ_P :	$\mathbb{R}^+$	Angular distance between two teeth
$\varphi(t)$:	$\mathbb{R}_0^+$	Angular position of crank shaft
φ_0^P :	$\mathbb{R}_0^+$	Initial position offset of crank shaft at beginning of current phase
$\omega(t)$:	$\mathbb{R}_0^+$	Angular velocity of crank shaft
ω_0 :	$\mathbb{R}_0^+$	Initial angular velocity of crank shaft at beginning of current phase
α :	$\mathbb{R}$	Angular acceleration of crank shaft
t_0 :	$\mathbb{R}_0^+$	Time offset of current phase

3.3 Generator

Tasks:

- set angular acceleration α
- develop $\varphi(t)$ and $\omega(t)$
- generate signals O_P, O_S

Approach: Perform all relevant work in ISR for primary teeth. Simplify implementation by setting a new α only when O_P occurs. O_S timer is set in a corresponding (find an apt one) O_P instance. In the following, we use the expression *phase* to denote the time span between two changes of α. During a phase, α is constant.

3.3.1 Primary Teeth

The parameters used in the following calculations are explained in table 4. The occurence of a primary tooth is characterised by the following equation:

$$\varphi(t) - \varphi_0^P \equiv 0 \pmod{\Delta_P} \tag{19}$$

Through constraining a change of α to times where O_P occurs, we can simplify this equation and search for the k_P-th primary signal in a phase that is characterised by:

$$\varphi(t) = \varphi_0^P + k_P \Delta_P \tag{20}$$

Solve equation (20):

$$\frac{1}{2}\alpha(t-t_0)^2 + \omega_0(t-t_0) + \varphi_0^P = \varphi_0^P + k\Delta_P \tag{21}$$

$$\Leftrightarrow \quad \frac{1}{2}\alpha t^2 + \omega_0 t - \frac{1}{2}\alpha t_0^2 - \omega_0 t_0 - k\Delta_P = 0 \tag{22}$$

$$\Leftrightarrow \quad t_{1/2} = \frac{-\omega_0 \pm \sqrt{\omega_0^2 + 2\alpha\left(\frac{1}{2}\alpha t_0^2 + \omega_0 t_0 + k\Delta_P\right)}}{\alpha} \tag{23}$$

Table 5: Additional parameters for secondary teeth calculations

φ_0^S :	$\mathbb{R}_0^+$	Initial position offset of next tooth
Δ_S :	$\mathbb{R}^+$	Angular distance between two secondary teeth
ϕ_S :	$\mathbb{R}_0^+$	Angular distance between next secondary tooth and primary tooth at which last phase change was triggered

We are only interested in the right-hand solution, as $t(k)$ must be a monotonically increasing function:

$$t(k) = \frac{-\omega_0 + \sqrt{\omega_0^2 + 2\alpha\left(\frac{1}{2}\alpha t_0^2 + \omega_0 t_0\right) + 2\alpha k \Delta_P}}{\alpha} \tag{24}$$

Parts of the discriminant must only be calculated when a new phase begins. Defining two constants

$$D_1 := \omega_0^2 + 2\alpha\left(\frac{1}{2}\alpha t_0^2 + \omega_0 t_0\right) \tag{25}$$

$$D_2 := 2\alpha\Delta_P \tag{26}$$

we can simplify $t(k)$:

$$t(k) = \frac{-\omega_0 + \sqrt{D_1 + D_2 k}}{\alpha} \tag{27}$$

The above calculations apply mainly to the primary signal O_P. To generate O_P concurrently, a closer look is necessary. The basic approach is to perform all calculations only in the IRQ handler of the O_P routine. Concerning O_S, a phase shift parameter $\phi_S \in [0, \Delta_P)$ is introduced that describes the angular distance betweeen the secondary tooth and the preceding primary tooth.

3.3.2 Secondary Teeth

Calculations of the secondary teeth times require additional parameters that are summarised in table 5. Times for O_S can be developed in a similar manner, but the calculations will be a bit more complex, as a change of α will not necessarily overlap with an occurrence of O_S. Thus, O_S will occur any time when:

$$\varphi(t) - \varphi_0^S \equiv 0 \pmod{\Delta_S} \tag{28}$$

Ideally, the time of O_S should just be calculated when the preceeding primary tooth was triggered, to account for a possible change of α.

The k-th secondary signal in a single phase has the following property:

$$\varphi(t) = \varphi_0 + \phi_S + (k-1)\Delta_S \tag{29}$$

3.3.3 Implementation Notes

Time Units Use seconds.

Replace Multiplication by Addition Implementation should use equations (20) and (29): The k parameter will only implicitly be kept, instead implementation should simply advance the $k\Delta_P$ resp. $(k-1)\Delta_S$ products.

Keep Numbers small In the long rung, the angular position $\varphi(t)$ can grow to a very large number. Reset $\varphi(t)$ in regular intervals, e.g once per revolution, to avoid loosing precision.

Irrelevance of Phase Shift For the use case, the initial phasing of the crank shaft is irrelevant. Therefore, set $\varphi_0 := 0$.

Renormalisation Renormalisation is performed at $\varphi(t) = 0 \pmod 1$.

$$\omega_0 := \omega(t) \tag{30}$$
$$\varphi_0 := 0 \tag{31}$$
$$t_0 := t \tag{32}$$
$$\leftrightarrow t := 0 \tag{33}$$
$$\tag{34}$$

Secondary Tooth Let the secondary tooth reside directly after the third primary tooth at $\phi_S \in [3\Delta_P, 4\Delta_P)$.

Phase Change May happen at any primary tooth. Some phases are very short (1-2 teeth). Restricting phase changes to only a single tooth would make the discriminant in calculation of next t (eq. (27)) negative. Additional work:

$$\alpha := \alpha_N \tag{35}$$

Setting Secondary Tooth Timer Performed in ISR for second primary tooth. Depending on the actual ϕ_S, even the third ISR might suffice, but we want to be on the safe side.

4 Implementation

4.1 Preprocessor

Algorithm 1 shows the basic structure/functionality of the preprocessor tool. The following special cases are handled:

driveaway is detected if the *startspeed* of an operation is 0 and the *endspeed* is $\neq 0$.

standstill *start*- and *endspeed* of the operation are 0

clutch disengaged is found if the currend speed is $\neq 0$ and gear is 0.

gearchange if the gear of the current phase is different from the one of the previous phase.

Algorithm 1 Preprocessing of driving cycle

```
Require: OperationList contains all operation of the driving cycle, each oper-
  ation is a tuple (acceleration, startspeed, endspeed, duration, gear)
Ensure: PhaseList contains the corresponding phases for the generator
  procedure PREPROCESS(OperationList)
      for all op in OperationList do
          if driveaway then                        ▷ Phases according to sect. 2.4.2
              PhaseList.enqueue(0, t)                        ▷ t according to eq. (13)
              PhaseList.enqueue(α_N, op.duration−t)
          else if standstill then
              PhaseList.enqueue(±α_I, t)                          ▷ t until ω_I reached
              PhaseList.enqueue(0, op.duration−t)
          else if clutch disengaged then           ▷ Phases according to sect. 2.4.4
              PhaseList.enqueue(±α_I, t)                            ▷ until ω_I reached
              PhaseList.enqueue(0, op.duration−t)
          else if gearchange then                  ▷ Phases according to sect. 2.4.3
              PhaseList.enqueue(±α_I, 1/2 op.duration)
              PhaseList.enqueue(α_G, 1/2 op.duration)             ▷ α_G from eq. (17)
          else                             ▷ regular driving/acceleration/deceleration
              PhaseList.enqueue(angular acceleration, op.duration)
          end if
      end for
  end procedure
```

4.2 Generator

The generator has to implement two interrupt service routines, one for the primary tooth (alg. 2) and one for the secondary tooth (alg. 3). Most of the work is performed in the primary ISR when the signal is deactivated.

The following constants are additionally necessary:

TimeToTicks convert time values from solution of equations to timer ticks

Notes on implementation experience:

- Times for primary OC must be set relatively to previous primary
- Times for secondary OC should be set absolutely. Using relative numbers would increase complexity. Absolute number should be derived from previous primary time (trigger of calculation).

Algorithm 2 ISR for primary tooth

```
procedure PrimaryISR
    if pin activate then
        set deactivation time
        return
    else
        if k == 0 then                              ▷ Renormalise
            ω_0 ← ω(t)
            φ_0 ← 0
            t ← 0
        end if
        if phase change pending then                ▷ Change Phase
            α ← α_N
        end if
        calculate next t_P
        set primary activation time
        if k == 1 then                              ▷ set secondary timer
            calculate next t_S
            set secondary activation time
        end if
    end if
end procedure
```

Algorithm 3 ISR for secondary tooth

```
procedure SecondaryISR
    if pin activate then
        set deactivation time
        return
    else                                            ▷ do nothing
    end if
end procedure
```

Table 6: Urban cycle

Op. Nr.	Operation	Acc.	Speed	Dur.	Gear
1	Idling	-	-	11	6 s PM + 5 s K1
2	Acceleration	1,04	0-15	4	1
3	Steady speed	-	15	9	1
4	Deceleration	-0,69	15-10	2	1
5	Dec., clutch diseng.	-0,92	10-0	3	K1
6	Idling	-	-	21	16 s PM + 5 s K1
7	Acceleration	0,83	0-15	5	1
8	Gear change	-	-	2	1→ 2
9	Acceleration	0,94	15-32	5	2
10	Steady speed	-	32	24	2
11	Deceleration	-0,75	32-10	8	2
12	Dec., clutch diseng.	-0,92	10-0	3	K2
13	Idling	-	-	21	16 s PM + 5 s K1
14	Acceleration	0,83	0-15	5	1
15	Gear change	-	-	2	1→ 2
16	Acceleration	0,62	15-35	9	2
17	Gear change	-	-	2	2→ 3
18	Acceleration	0,52	35-50	8	3
19	Steady speed	-	50	12	3
20	Deceleration	-0,52	50-35	8	3
21	Steady speed	-	35	13	3
22	Gear change	-	-	2	3→ 2
23	Deceleration	-0,86	35-10	7	2
24	Dec., clutch diseng.	-0,92	10-0	3	K2
25	Idling	-	-	7	7 s PM

A Driving Cycle

Tables 6 and 7 present excerpts from "M6 COUNCIL DIRECTIVE of 20 March 1970 on the approximation of the laws of the Member States on measures to be taken against air pollution by emissions from motor vehicles" version from 01.01.2007. These can be found in the files `urban.ndc` resp. `extra-urban.ndc` in the `/data/` directory. The file `nefz.ndc` holds the whole driving cycle consisting of four times the urban cycle and once the extra-urban cycle.

Table 7: Extra-urban cycle

Op. Nr.	Operation	Acc.	Speed	Dur.	Gear
1	Idling	-	-	20	K1
2	Acceleration	0,83	0-15	5	1
3	Gear change	-	-	2	$1 \rightarrow 2$
4	Acceleration	0,62	15-35	9	2
5	Gear change	-	-	2	$2 \rightarrow 3$
6	Acceleration	0,52	35-50	8	3
7	Gear change	-	-	2	$3 \rightarrow 4$
8	Acceleration	0,43	50-70	13	4
9	Steady speed	-	70	50	5
10	Deceleration	-0,69	70-50	8	4 s.5 + 4 s.4
11	Steady speed	-	50	69	4
12	Acceleration	0,43	50-70	13	4
13	Steady speed	-	70	50	5
14	Acceleration	0,24	70-100	35	5
15	Steady speed	-	100	30	5*
16	Acceleration	0,28	100-120	20	5*
17	Steady speed	-	120	10	5*
18	Deceleration	-0,69	120-80	16	5*
19	Deceleration	-1,04	80-50	8	5*
20	Dec., clutch diseng.	-1,39	50-0	10	K5
21	Idle	-	-	20	PM