Informal Document **GRB- 61-09**
61st GRB, agenda item 7

Transmitted by the experts from France

(France)

Method of Deceleration Measuring and Data Processing for Tyre Rolling Resistance Determination.

Comparison of Rolling resistance measurements between dedicate and non-dedicated Rolling resistance machine.

The report of ad-hoc working group organized in accordance with the recommendation of the 59th GRB session

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1. Introduction

Following the previous ad-hoc report (GRB59-07) ECE/TRANS/WP.29/GRB/59-07 and after the introduction of the method of deceleration measuring and data processing for tire rolling resistance determination using the dω/dt form ("Deceleration Calculator") proposed by NAMI and accepted by GRB, the expert from UTAC (France) decided to conduct a new series of tests base on C2 and C3 tires in order to complete the study. The NAMI (the Russian Federation) provided the complete tool set and "Deceleration Calculator" in order to perform new measurements.

The previous report focused on the assessment of the theorical justification of the method used in the alternative method using dω/dt form, its algorithm of data processing, equation system solving and statistical assesment of the method. The assessment was based on a C1 tire with the use of a specialized test machine (MTS-UTAC) in one hand and on a test machine not specially designed for those measurements (HAWITEC-UTAC) in the other hand. For C3 and C2, experimental data consideration was made based on data obtained by NAMI from measurements made previously on their own machines.

The aim of this new study, is to perform complementary tests with one C2 and one C3 tire on a specialized test machine (MTS-UTAC) and the same C2 and C3 on a test machine not specially designed for those measurements (HAWITEC-UTAC) equipped with the NAMI data logger NAMI-357. The objectives are:

1. To confirm a repeatability on the measurements in accordance with the requirement of ECE R117.
2. To compare values recorded on the two machines with the same C2 and C3 tires.

2. Tires selection

Two tires have been purchased in order to perfom the study. Below the technical specifications, references and expected Rolling Resistance Coefficient. (RRC).

Trademark	Type	Load/speed Index	Sizes	Expected Rolling Resistance Coefficient (RRC)
GOODYEAR / FUELMAX S	C3	156 L*	315/80R22,5	4.1 ≤ RRC ≤ 5.0
MICHELIN / AGILIS +	C2	104 R	195/65R16C	6.8 ≤ RRC ≤ 8.0

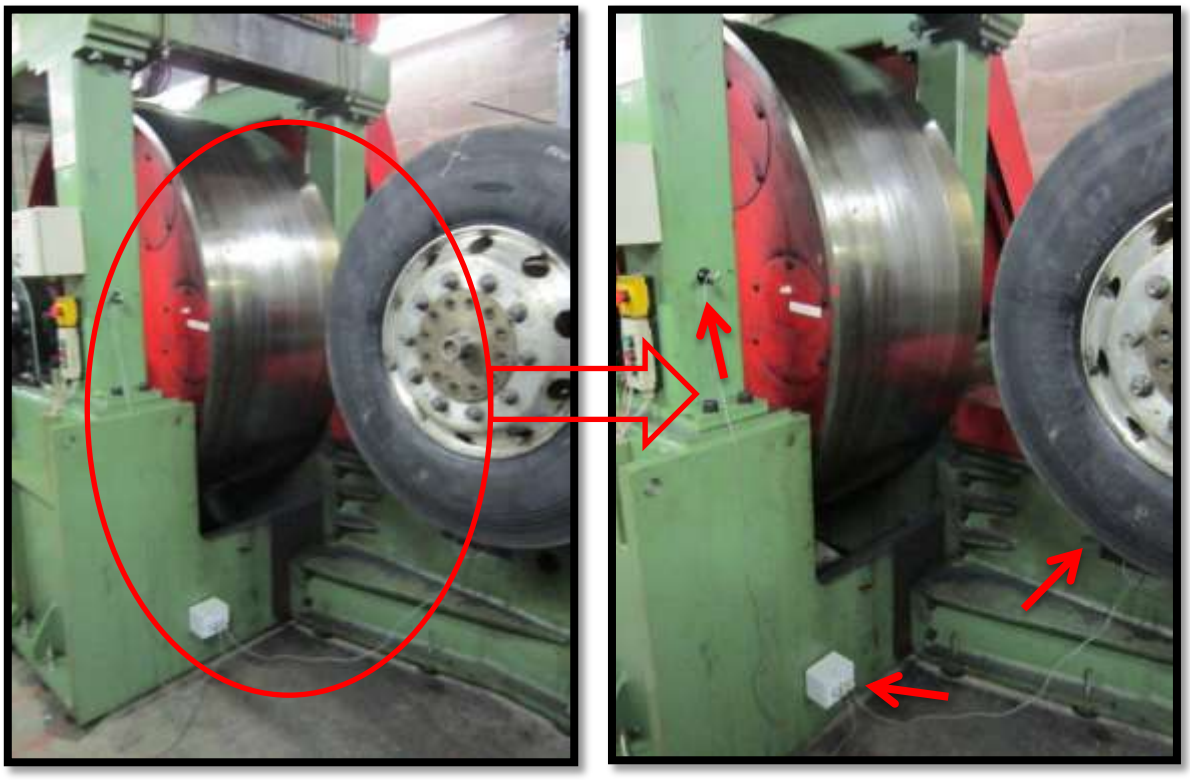
3. Measurements & tests processing

All the tests conducted during this program have been performed according to ECE R117 including conditioning of the tires and interval between 2 tests.
On the HAWITEC-UTAC machine additional skim test was performed for the measurement of tire spindle parasitic losses. On both machine (MTS-UTAC and HAWITEC-UTAC) the force applied during skim load was in accordance to the ECE R117 with the use of 150N for the C2 and 400N for the C3.
For each C2 and C3 tires, two measurements have been performed on both machine.

● The tests conducted on the specialized test machine (MTS-UTAC) has been carried out under Torque method due to the official method declared for this machine.

Example of tires (C2 & C3) fitting on MTS-UTAC rolling resistance machine

● The tests conducted on the HAWITEC-UTAC machine was realized under Deceleration method fully equipped with the NAMI measurement kit "data logger NAMI-357" and "Deceleration Calculator" including drum and tire sensors. (See red arrows on pictures below).



Example of tires (C2 & C3) fitting on HAWITEC-UTAC Load/speed machine and Data Logger NAMI-357

4. Data analysis

In order to perform the tests we have followed the user instructions kindly provided by NAMI with the measurement kit "data logger NAMI-357" and "Deceleration Calculator". The document is in the annex 01 of this report. Regarding the "Deceleration Calculator" used for those measurements it was based on the original version available under the link (http://nami.ru/upload/calculator.zip) customed by NAMI for easy use with three additional functions listed here:

- Control of data logger NAMI-357,
- Full cycle of calculation up to Cr 25 value,
- Measurements and calculation integrating into a common simple procedure.

4.1 Study for C2 Tire

On C2 tire, the results for the two measurements with the machine (MTS-UTAC) dedicated to rolling resistance measurement are located in the scale of expected CRR (Labelling) mentioned in § 2.

First C2 test (table 1) : 6.8 ≤ **7.35** ≤ 8.0 N/kN
Second C2 Test (table 2) : 6.8 ≤ **7.23** ≤ 8.0 N/kN

Despite the results here are R117-oriented and not aligned according to R1222, it show values in the target gap. However the repeatability of the two measurements is not good as required by R1222 (table 6) but it is due to a short number of tests (a standard deviation should be at σm ≤ 0,070). Usually it takes 4 measurements on a same tire to state on a value (by saving the 3 last for computing).

Table 1

MTS

Station #1 ISO 28580 Rolling Resistance Report

Torque Method

Test Request :	DR C2		**Test Date:**	11/10/14	
Test Procedure:	ISO28580 C2LImax121Couple		**Test Time:**	08:30 AM	
Tire Class:	Passenger		**Tire Construction Code:**	Radial	
Tire Manufacturer:	MICHELIN		**Tire DOT Code:**	B5CV 008X	
Tire Brand:	AGILIS		**Tire Type:**	Normal	
Tire Size:	195/65R16C				
			Wheel Diameter:	16	in
Reference Load:	8826	N	**Rim Width:**	6,0	in
Reference Inflation:	475	kPa	**Wheel Plane Offset:**	ET50	
Maximum Load:	11000	N	**Adaptor Id:**	ET50	
Maximum Inflation:	500	kPa			
			Tire Info 1	104/102	
Initial Inflation:	475,00	kPa	**Tire Info 2**	R	
Design Tire Diameter:	665,6	mm	**Tire Info 3**	4312,00	
Tire Identifier:	DR C2		**Tire Info 4**	non	

	Test Condition Information						Skim Information			Tare Information		Rolling Resistance					
Test Point	V_r	T_a	RPK	P_t	F_z	T_D	RL	F_{zs}	F_{pl}	F_{zt}	T_{Dt}	F_{xc}	F_R	F_{R25}	F_{R02}	F_{Ralign}	C_R
	kph	degC		kPa	N	N-m	m	N	N-m	N	N-m	N	N	N	N	N	N/kN
1	79,98	24,95	455,3139	4,98	7500,3	70,50	0,3	148,4	15,4	15,84	11,90	70,50	55,12	55,10	55,10	55,10	7,347

Table 2

MTS

Station #1 ISO 28580 Rolling Resistance Report

Torque Method

Test Request :	DR C2		**Test Date:**	11/14/14	
Test Procedure:	ISO28580 C2LImax121Couple		**Test Time:**	10:04 AM	
Tire Class:	Passenger		**Tire Construction Code:**	Radial	
Tire Manufacturer:	MICHELIN		**Tire DOT Code:**	B5CV 008X	
Tire Brand:	AGILIS		**Tire Type:**	Normal	
Tire Size:	195/65R16C				
			Wheel Diameter:	16	in
Reference Load:	8826	N	**Rim Width:**	6,5	in
Reference Inflation:	475	kPa	**Wheel Plane Offset:**	ET50	
Maximum Load:	11000	N	**Adaptor Id:**	ET50	
Maximum Inflation:	500	kPa			
			Tire Info 1	104/102	
Initial Inflation:	475,00	kPa	**Tire Info 2**	R	
Design Tire Diameter:	665,6	mm	**Tire Info 3**	4312,00	
Tire Identifier:	DRC2b		**Tire Info 4**	non	

	Test Condition Information						Skim Information			Tare Information		Rolling Resistance					
Test Point	V_r kph	T_a degC	RPK	P_t kPa	F_z N	T_D N-m	RL m	F_{zs} N	F_{pl} N-m	F_{zt} N	T_{Dt} N-m	F_{xc} N	F_R N	F_{R25} N	F_{R02} N	F_{Ralign} N	C_R N/kN
1	79,97	25,15	454,5249	4,63	7501,4	69,57	0,3	148,1	15,4	14,27	11,95	69,57	54,17	54,23	54,23	54,23	7,230

The results for the two measurements with the machine (HAWITEC-UTAC) not dedicated to rolling resistance measurement are not located in the scale of expected CRR (Labelling) mentioned in § 2.

First C2 test (table 3) : 3.880 instead of 6.8 ≤ **RRC** ≤ 8.0 N/kN
Second C2 Test (table 4) : 4.243 instead of 6.8 ≤ **RRC** ≤ 8.0 N/kN

For those measurements, the CRR values are around half the values recorded with MTS-UTAC machine. The repeatability of the two measurements is very poor. Although we have got only 2 measurements, the standard deviation is really high wide (over 0,100, see table 6).

Table 3

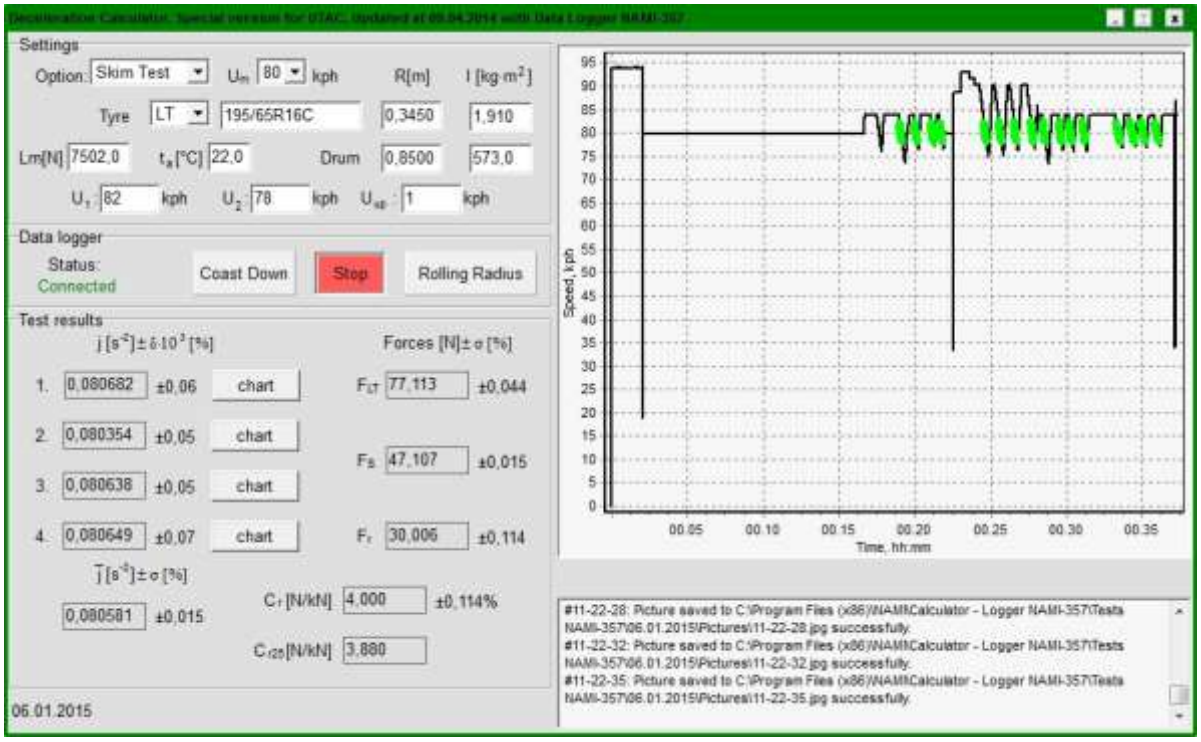


Table 3

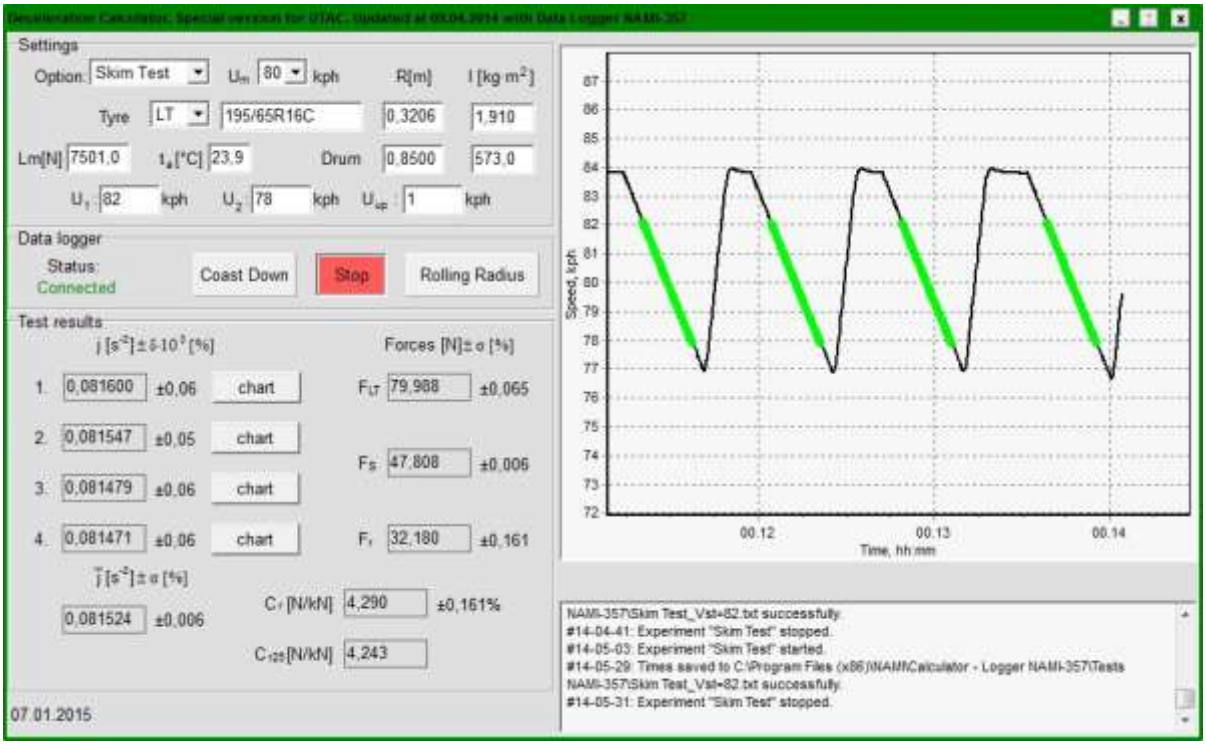


Table 6

Test N°	CRR C2 Tire N/kN		Δ, %
	MTS-UTAC	HAWITEC-UTAC	
1	7,347	3,880	52,81%
2	7,230	4,243	58,69%
Average	7,289	4,062	55,72%
Std DEV	0,083	0,257	

In the view of Forces (Fr in Newton) it is the same observation and a confirmation of low values on HAWITEC-NAMI machine with a difference of 23.55 N between the two type of machines. (table 7)

Table 7

Test N°	Fr C2 Tire (Newton)		Δ in N
	MTS-UTAC	HAWITEC-UTAC	
1	55,120	30,006	25,11
2	54,170	32,180	21,99
Average	54,645	31,093	23,55

4.2 Study for C3 Tire

As observed on C2 study fo C3 tire, the results gived by the machine (MTS-UTAC) dedicated to rolling resistance measurement are located in the scale of expected CRR (Labelling) mentioned in § 2.

First C3 test (table 8) : 4.1 ≤ **4.85** ≤ 5.0 N/kN
Second C3 Test (table 9) : 4.1 ≤ **4.74** ≤ 5.0 N/kN

As described for the C2 the results here are R117 and not aligned by R1222 it show values in the target gap. Here again we see that the repeatability of the two measurements are not strong as required by R1222 but closer to the requirement. of σm ≤ 0,070. (table 12)

Table 8

Station #2 ISO 28580 Rolling Resistance Report

Torque Method

Test Request :	AFFSAS1401479 A		**Test Date:**	8/28/14	
Test Procedure:	ISO28580 C3 short 80kmh		**Test Time:**	09:45 AM	
Tire Class:	Highway Truck/Bus		**Tire Construction Code:**	radial	
Tire Manufacturer:	GOODYEAR		**Tire DOT Code:**	NJ72CT1W	
Tire Brand:	FUELMAX S		**Tire Type:**	NORMAL	
Tire Size:	315/80R22.5				
			Wheel Diameter:	22,5	in
Reference Load:	39226	N	**Rim Width:**	9,0	in
Reference Inflation:	850	kPa	**Wheel Plane Offset:**	A1	
Maximum Load:	40000	N	**Adaptor Id:**	A1	
Maximum Inflation:	900	kPa			
			Tire Info 1	156/150	
Initial Inflation:	850,00	kPa	**Tire Info 2**	L	
Design Tire Diameter:	1078,4	mm	**Tire Info 3**	2714,00	
Tire Identifier:	1479A2		**Tire Info 4**	#######	

	Test Condition Information						Skim Information			Tare Information		Rolling Resistance					
Test Point	V_r kph	T_a degC	RPK	P_t kPa	F_z N	T_D N-m	RL m	F_{zs} N	F_{pl} N-m	F_{zt} N	T_{Dt} N-m	F_{xc} N	F_R N	F_{R25} N	F_{R02} N	F_{Ralign} N	C_R N/kN
1	80,04	26,76	302,9302	-0,48	33340,8	177,23	0,5	388,5	17,3	40,23	11,77	177,23	159,91	161,59	161,59	161,59	4,847

Table 9

Station #2 ISO 28580 Rolling Resistance Report

Torque Method

Test Request :	DRC3		**Test Date:**	1/5/15	
Test Procedure:	ISO28580 C3 short 80kmh		**Test Time:**	09:28 AM	
Tire Class:	Highway Truck/Bus		**Tire Construction Code:**	radial	
Tire Manufacturer:	GOODYEAR		**Tire DOT Code:**	NJ72CT1W	
Tire Brand:	FUELMAX S		**Tire Type:**	NORMAL	
Tire Size:	315/80R22.5				
			Wheel Diameter:	22,5	in
Reference Load:	39226	N	**Rim Width:**	9,0	in
Reference Inflation:	850	kPa	**Wheel Plane Offset:**	A1	
Maximum Load:	40000	N	**Adaptor Id:**	A1	
Maximum Inflation:	900	kPa			
			Tire Info 1	156/150	
Initial Inflation:	850,00	kPa	**Tire Info 2**	L	
Design Tire Diameter:	1069,0	mm	**Tire Info 3**	2714,00	
Tire Identifier:	DRC3a		**Tire Info 4**	#######	

	Test Condition Information						Skim Information			Tare Information		Rolling Resistance					
Test Point	V_r kph	T_a degC	RPK	P_t kPa	F_z N	T_D N-m	RL m	F_{zs} N	F_{pl} N-m	F_{zt} N	T_{Dt} N-m	F_{xc} N	F_R N	F_{R25} N	F_{R02} N	F_{Ralign} N	C_R N/kN
1	80,04	26,04	0,0000	1,72	33347,0	174,80	0,5	393,5	17,6	34,18	11,78	174,80	157,20	158,18	158,18	158,18	4,743

Regarding the results for the measurements with the machine (HAWITEC-UTAC) not dedicated to rolling resistance measurement are not located in the scale of expected CRR (Labelling) mentioned in § 2.

First C3 test (table 10) : 2.584 instead of 4.1 ≤ **RRC** ≤ 5.0 N/kN
Second C2 Test (table 11) : 2.649 instead of 4.1 ≤ **RRC** ≤ 5.0 N/kN

For those measurement, the CRR values appear around half of the values recorded with MTS-UTAC machine. The repeatability level of the two measurements here is much better. The standard deviation is under 0,070 , see table 12.

Table 10

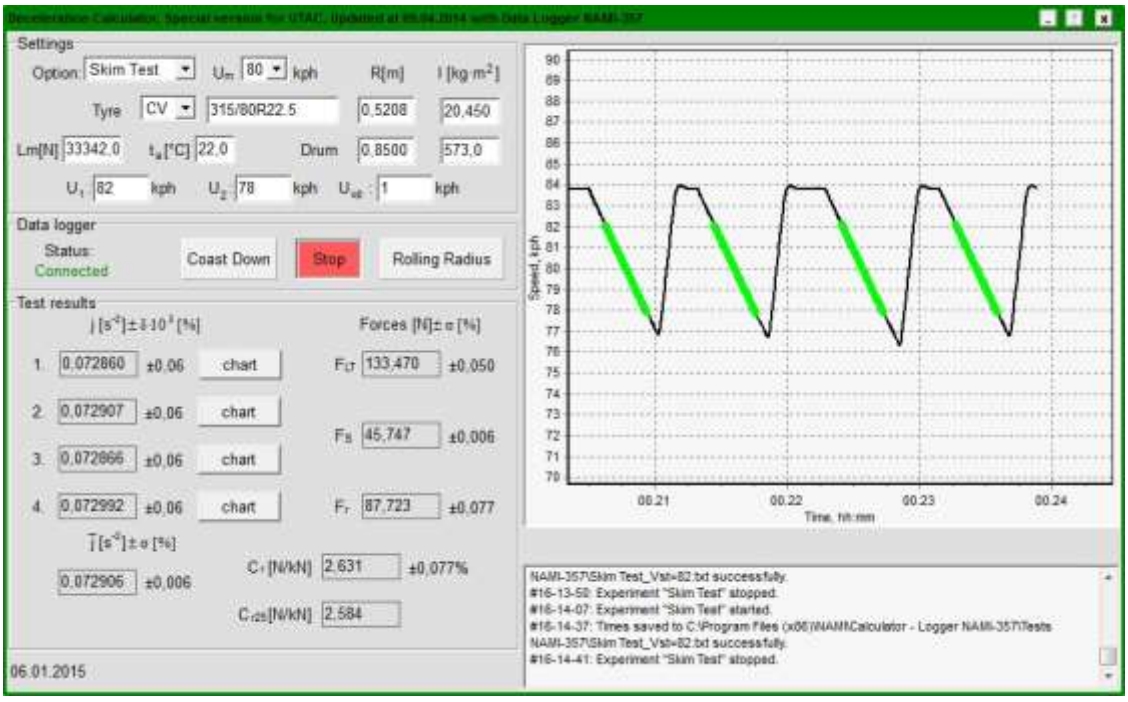


Table 11

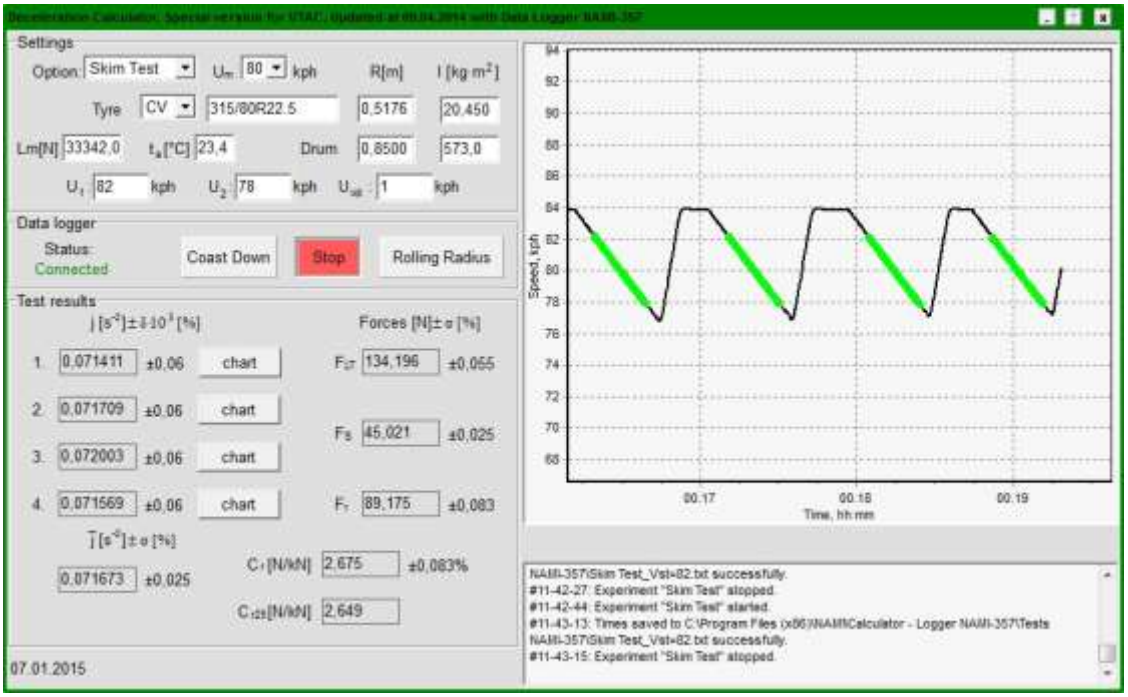


Table 12

Test N°	CRR C3 Tire N/kN		Δ, %
	MTS-UTAC	HAWITEC-UTAC	
1	4,847	2,584	53,31%
2	4,743	2,649	55,85%
Average	4,795	2,617	54,57%
Std DEV	0,074	0,046	

When we observe the Forces (Fr in Newton) between the two types of machines, there is a difference of 70.11 N for the C3 tire (table 13). This statement indicates that the Forces (Fr) measured, proportionally increased with the load applied during the test.

Table 13

Test N°	Fr C3 Tire (Newton)		Δ in N
	MTS-UTAC	HAWITEC-UTAC	
1	159,910	87,723	72,19
2	157,200	89,175	68,03
Average	158,555	88,449	70,11

5 Conclusions

Testing those two tires C2 and C3 on the two machines highlight some disparity between the test values measured on the MTS-UTAC and HAWITEC-UTAC machines.
A similar test with the same tires (as used by UTAC) could be conducted on another Load and Speed machine for further investigations.

Annex 01

Deceleration Calculator. Special version for UTAC.

(short manual)

This version in comparison with base one (http://nami.ru/upload/calculator.zip) has three additional functions:
1. control of data logger NAMI-357;
2. full cycle of calculations up to C_{r25} value;
3. measurements and calculations integrating into common simple procedure.

How to install the program:
1. Run Setup Calculator - Logger NAMI-357.exe;
2. Follow the instructions on the screen.

Explanation to the main window

Main window structure of the program is very simple and clear from survey. Though:

Abbreviations
PC – passenger car tyre;
LT – light truck tyre (in tyre class designation only);
CV – commercial vehicle tyre;
Forces in N:
$\mathbf{F_{LT}}$ – loaded tyre resistance;
$\mathbf{F_T}$ – tyre-wheel-hub parasitic losses;
$\mathbf{F_D}$ – drum (machine) parasitic losses;
$\mathbf{F_S}$ – skim test parasitic losses;
$\mathbf{F_r}$ – rolling resistance;

j – deceleration value in s^{-2};
$\boldsymbol{\delta}$ – standard deviation, characterizes quality of approximation of experimental distance-time functions in percent;
$\boldsymbol{\sigma}$ – standard deviation of j value relatively expectation in percent.

"Settings" section serves for initial data insertion before start of testing.
Option – must be chosen correspondently to the test machine regime,
$\mathbf{U_m}$ – (80 or 60 km/h) main speed for resistance calculations.

Tyre classes selection (**PC, LT, CV**) serves for changing coefficients in formula C_{r25}.

R (R_t) of tyre is rolling radius which must be inserted manually as a result of dividing of running distance by tyre revolution number and by 2π. Another way: press the button **"Rolling Radius"** at second half of warm up process and after several seconds R_t value will appears in correspondent field. Press again (several times; 3 or 4 times is enough) and assemble averages will appears. The measurement base of R_t is 200 drum revolutions.

t_a [°C] – ambient temperature may be inserted during measurement cycle or after it and then C_{r25} data will appears.

I – drum inertia in right lower corner of upper section must include motor and transmission inertia.

U_1 and **U_2** are the borders of a test speed range.

U_{up} – speed bounce for bringing measurement system into readiness for parameters recording i.e. if the drum peripheral speed has reached value equal U_1+U_{up} at coast down, data recording will be started at speed U_1.

It is important: test machine program should include reaching the speed $U>U_1+U_{up}$.

For example: if $U_1=82$ and $U_{up}=1$ maximum test machine speed before coastdown must be not less than 84 km/h.

"Data logger" section serves for measurements control.

Press **"Coast Down"** button to actuate of readiness stage of the system for starting measurements in accordance with chosen option.

Press button **"Stop"** *to stop measurements within actuated option before start of the next chosen option*. This button may be need also for stopping measurements after test number less then 4.

Press "Coast Down" button for starting measurements within another option.

Use the button **"Rolling Radius"** as described in "Setting Section".

Test results section contains the fields for indicating test results such as $j=d\omega/dt$, forces of resistance F and C_r coefficients with estimations by δ and σ.

Note: If number of measurements exceed 4 test result №1 will be substituted by result №5 etc. Maximum test number is not limited.

Column j indicates the data corresponding to the chosen option.

Pressure the button "chart" opens the graph "time-distance" with lens.

σ – is standard deviation of 3 or 4 measurements (if less σ does not calculated and not appears). If number of measurements is more then 4 σ reflects only 4 results indicated on the screen.
The measurements are accommodating by time-speed graph.
Note: to stop measurements and calculations after 1, 2 or 3 tests press the button "Stop" and j value will appears.
Forces of resistance will be quantized according as type experiment options will be finished. When combinations F_{LT}, F_S or F_{LT}, F_T, F_D are completed rolling resistance force F_r and C_r coefficients appear. If t_a data is inserted, C_{r25} data appears too.

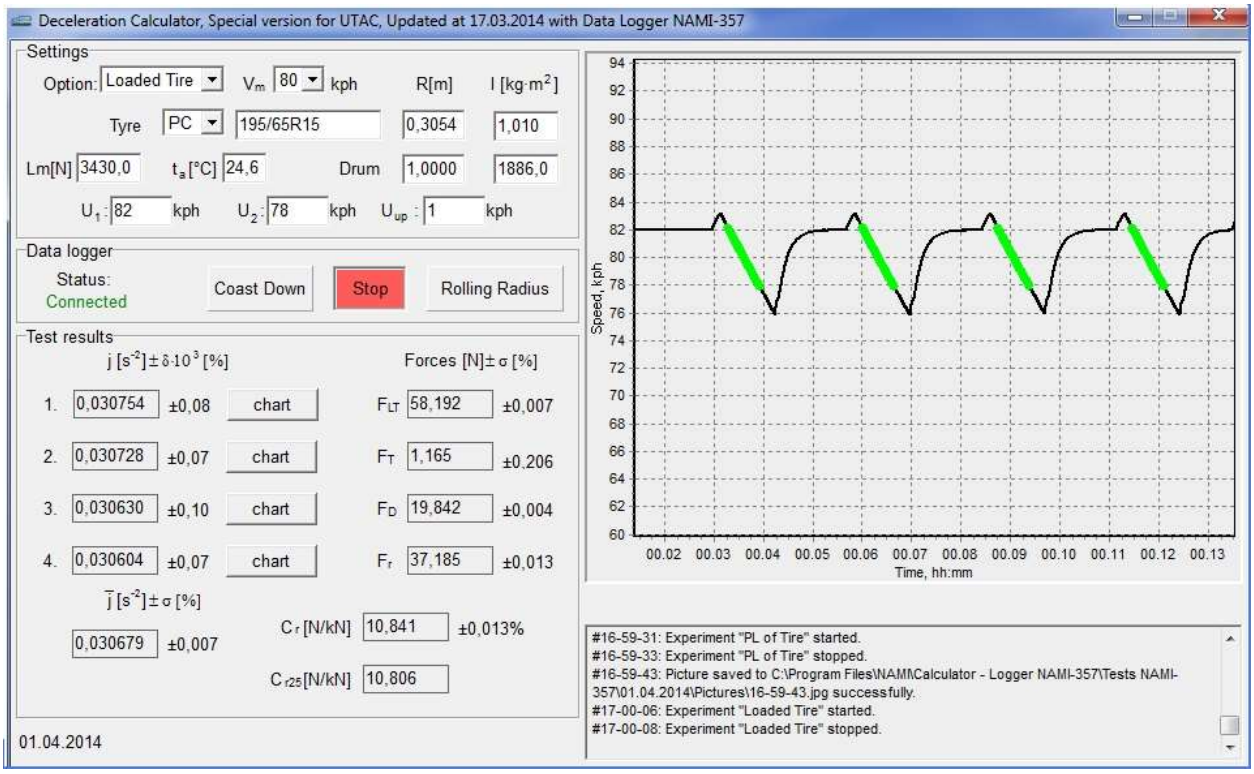
Sequence of operator actions

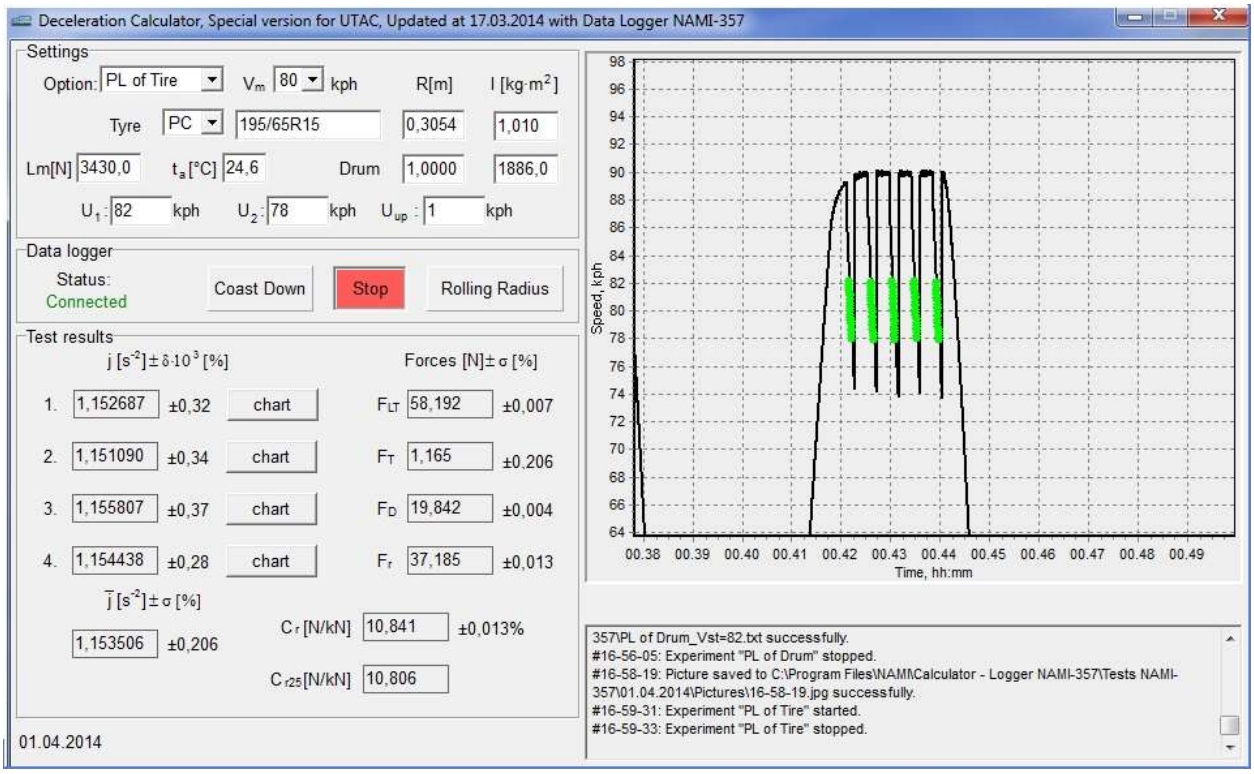
1. Install logger NAMI-357 and its sensors on test machine (fig. 1), install red module of radio channel on computer (black module is mounted inside of device box).
2. Open the "Deceleration Calculator" program; insert initial data into fields of setting section.
3. At second half of warm-up press the button "Rolling Radius" and record R_t data. Repeat measurements 3-4 times.
4. Choice option "Loaded Tyre" accordingly to the test machine algorithm.

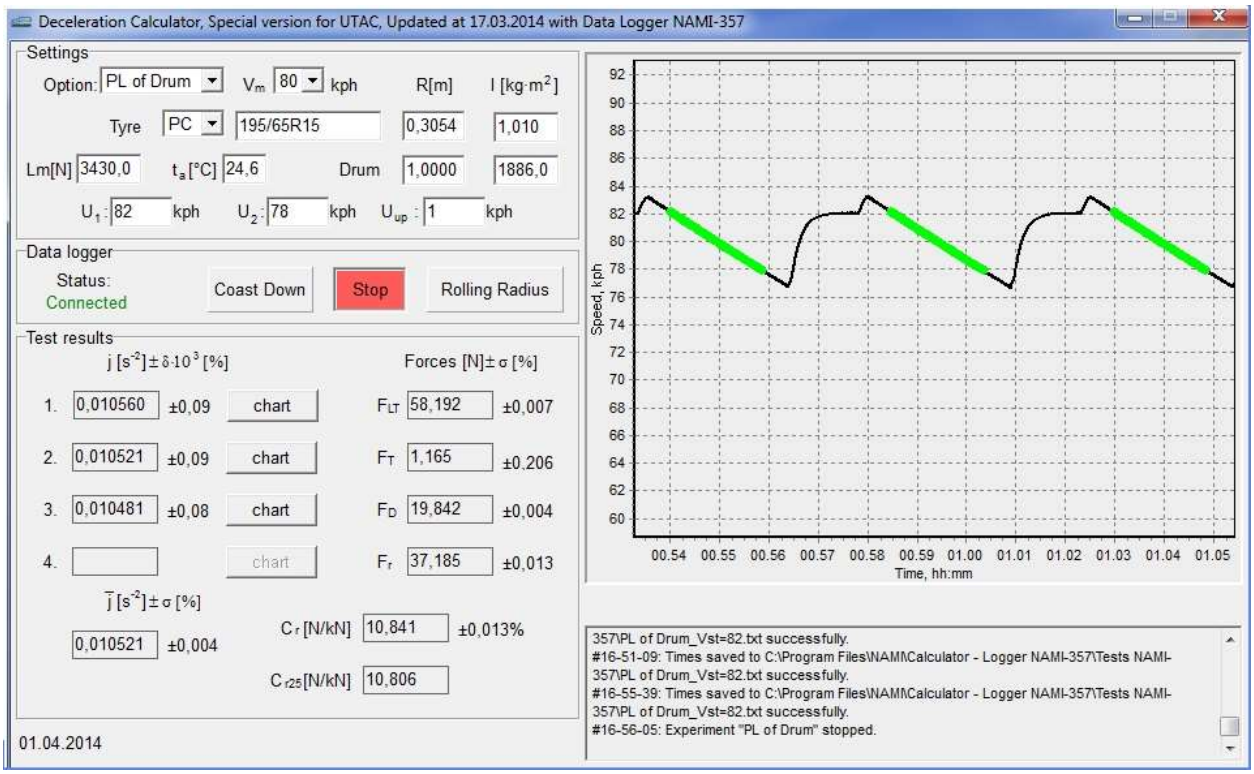
When the warm-up will be finished and drum speed in *initial phase of coasting* will reaches value equal U_1+U_{up} the recording of deceleration j will be started.

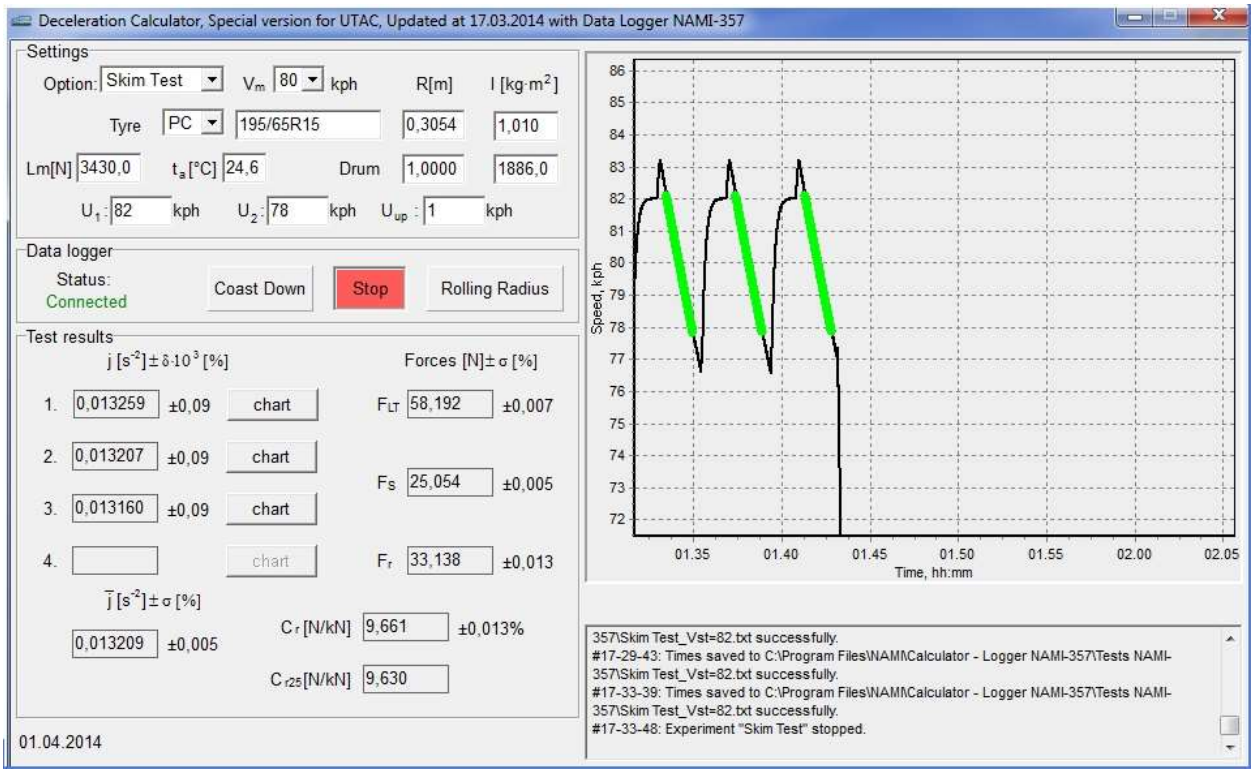
5. After finalising the measurements within option "Loaded Tyre" press "Stop" button and choice another option accordingly to test plan and press button "Coast down".
6. Finalize test measurements accordingly to test plan pressing the button "Stop".
7. To save test results in memory choice the screens desired using options switcher and pressing the button "Print screen".

Appendix 1: Listings of examples of test results print screen.






Deceleration Calculator, Special version for UTAC, Updated at 17.03.2014 with Data Logger NAMI-357
Settings
Option: PL of Drum
Vm 80 kph
R[m]
I [kg·m²]
Tyre PC 195/65R15 0,3054 1,010
Lm[N] 3430,0 ta[°C] 24,6 Drum 1,0000 1886,0
U1: 82 kph U2: 78 kph Uup: 1 kph
Data logger
Status: Connected
Coast Down
Stop
Rolling Radius
Test results
j [s⁻²] ± δ·10³ [%]
Forces [N] ± σ [%]
1. 0,010560 ±0,09 chart FLT 58,192 ±0,007
2. 0,010521 ±0,09 chart FT 1,165 ±0,206
3. 0,010481 ±0,08 chart FD 19,842 ±0,004
4. chart Fr 37,185 ±0,013
j̄ [s⁻²] ± σ [%]
0,010521 ±0,004
Cr [N/kN] 10,841 ±0,013%
Cr25 [N/kN] 10,806
01.04.2014
Speed, kph
Time, hh:mm
357\PL of Drum_Vst=82.txt successfully.
#16-51-09: Times saved to C:\Program Files\NAMI\Calculator - Logger NAMI-357\Tests NAMI-357\PL of Drum_Vst=82.txt successfully.
#16-55-39: Times saved to C:\Program Files\NAMI\Calculator - Logger NAMI-357\Tests NAMI-357\PL of Drum_Vst=82.txt successfully.
#16-56-05: Experiment "PL of Drum" stopped.


Deceleration Calculator, Special version for UTAC, Updated at 17.03.2014 with Data Logger NAMI-357
Settings
Option: Skim Test
Vm 80 kph
R[m]
I [kg·m²]
Tyre PC 195/65R15 0,3054 1,010
Lm[N] 3430,0 ta[°C] 24,6 Drum 1,0000 1886,0
U1: 82 kph U2: 78 kph Uup: 1 kph
Data logger
Status: Connected
Coast Down
Stop
Rolling Radius
Test results
j [s⁻²] ± δ·10³ [%]
Forces [N] ± σ [%]
1. 0,013259 ±0,09 chart FLT 58,192 ±0,007
2. 0,013207 ±0,09 chart
3. 0,013160 ±0,09 chart Fs 25,054 ±0,005
4. chart Fr 33,138 ±0,013
j̄ [s⁻²] ± σ [%]
0,013209 ±0,005
Cr [N/kN] 9,661 ±0,013%
Cr25 [N/kN] 9,630
01.04.2014
Speed, kph
Time, hh:mm
357\Skim Test_Vst=82.txt successfully.
#17-29-43: Times saved to C:\Program Files\NAMI\Calculator - Logger NAMI-357\Tests NAMI-357\Skim Test_Vst=82.txt successfully.
#17-33-39: Times saved to C:\Program Files\NAMI\Calculator - Logger NAMI-357\Tests NAMI-357\Skim Test_Vst=82.txt successfully.
#17-33-48: Experiment "Skim Test" stopped.

Appendix 2: **Formulae used** for additional calculations.

Rolling radius:

$$R_t = \frac{200R}{z_t}, \quad (1)$$

where z_t – number of tyre revolution during 200 drum revolutions.

Standard deviation as estimation of regression quality.

$$\delta = \sqrt{\frac{1}{z_{max} - 1} \sum_{1}^{z_{max}} \left(\frac{z}{z_z} - 1\right)^2} \, 100\%, \quad (2)$$

where: z_{max} – maximum of rotating body revolution during coast down,

z – current number of body revolution (integer),

z_z – the value of regression function at revolution number z (fractional).

Standard deviation of n measurements of j:

$$s = \sqrt{\frac{1}{n-1} \sum_{1}^{n} (j_i - \bar{j})^2}, [s^{-2}] \quad (3)$$

where:

$$\bar{j} = \frac{1}{n} \sum_{1}^{n} j_i,$$

Standard deviation of n measurements of j and of F[1] in percent:

$$\sigma = s \frac{100}{\bar{j}} \%, \quad (4)$$

Standard deviation of rolling resistance force:

$$s_{Fr} = \sqrt{s_{LT}^2 + s_T^2 + s_D^2}, [N] \quad (5)$$

where: s_{LT}, s_t and s_D – components of s_{Fr} and equal,

$$s_{LT} = \sigma_{LT} \frac{F_{LT}}{100}; \; s_T = \sigma_T \frac{F_T}{100}; \; s_D = \sigma_D \frac{F_D}{100}. \quad (6)$$

Standard deviation of rolling resistance force in percent:

$$\sigma_{FR} = s_{Fr} \frac{100}{F_r}, [\%] \quad (7)$$

[1] See formulae (11) – (14)

Substitution of (5) and (6) into (7) yields:

$$\sigma_{FR} = \frac{1}{F_R}\sqrt{(\sigma_{LT}\bar{J}_{LT})^2 + (\sigma_T\bar{J}_T)^2 + (\sigma_D\bar{J}_D)^2}, [\%] \quad (8)$$

Note: If skim test option is used formula (8) takes a form:

$$\sigma_{Fr} = \frac{1}{F_r}\sqrt{(\sigma_{PL}\bar{J}_{PL})^2 + (\sigma_S\bar{J}_S)^2}, [\%] \quad (9)$$

$$\dot{I}_\Sigma = I_D + I_t\left(\frac{R}{R_t}\right)^2, [kg\ m^2] \quad (10)$$

$$F_{LT} = \bar{J}_{LT}\dot{I}_\Sigma, [N] \quad (11)$$

$$F_S = \bar{J}_S\dot{I}_\Sigma, [N] \quad (12)$$

$$F_T = \bar{J}_T I_T, [N] \quad (13)$$

$$F_D = \bar{J}_D\dot{I}_D, [N] \quad (14)$$

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