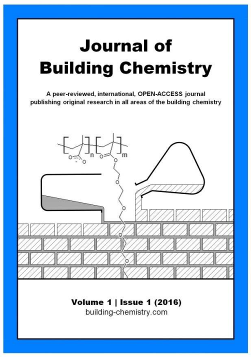

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Zero shear viscosity estimation using a computer simulation of Van der Poel's nomograph

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Abstract

The properties of asphalt mixtures depend both on the properties and the proportions of the components. Rutting resistance is related to the binder property called zero shear viscosity (ZSV). This paper presents a new method for estimating ZSV based on penetration and softening point tests by using a computer simulation of Van der Poel's nomograph. The results have been compared with literature data. Furthermore, for the purposes of the analysis presented in this paper, a computer simulation of the nomograph was developed. The results of simulation are presented in Appendix 1.

Keywords: Zero shear viscosity; Van der Poel's nomograph; rutting resistance; computer simulation

1. Introduction

Due to the increasing load on roads caused by vehicle traffic, pavement construction must be able to meet higher requirements. The target is to reach the highest possible durability with the lowest cost. The durability of currently used solutions depends mainly on proper material selection and performance quality. In the case of asphaltic mixtures, bitumen plays a key role. Asphalt consists of a macromolecular hydrocarbon mixture, including aliphatic, naphthenic and aromatic materials (Piłat and Radziszewski 2010). These components are classified to one of three groups: asphaltenes (brown or black substances, softening point temperature of about 150-200°C, present in the oil-dispersed phase), resins (solid or semi-solid with a brown color, which affect the adhesion of the asphalt to aggregates, toughness and ductility) and oils (the hydrocarbon fraction of asphalt, light brown in color, composed of paraffin-naphthenic and aromatic hydrocarbons, and responsible for the flexibility of asphalt) (Trzaska 2014). The proportions of these asphalt components determine its properties at different temperatures. Using various tests, a number of bitumen properties can be defined. This is done to precisely describe the criteria that should be met by asphalts designed for particular uses. Some correlations occur between the results of different tests, which allow for a prediction of the outcome of complex tests by using the results of simpler ones. For example, using Van der Poel's nomograph, asphalt stiffness can be determined at a given temperature and load time. Conducting this estimation requires knowledge of the two basic properties of asphalt, i.e. the softening point and penetration (e.g. at 25°C).

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The mechanical properties of asphalt depend on the load time/load frequency as well as the temperature. These properties can be described using visco-elastic constitutive models, such as the Burger, Prony or Huet-Sayegh model (Di Mino et al. 2014; Zbiciak 2013), which assess the asphalt response under different types of load during a test or construction analysis. Constitutive model parameters are usually identified using dynamic tests, but these are expensive and time-consuming. Recently, Zbiciak et al. (2015) presented a simplified method for estimating the rheological parameters of asphaltic mixtures based on their composition, using Van der Poel's nomograph. This approach can also be used for bitumen alone. The determined parameters can be used to predict asphalt properties usually obtained from more complex tests. This article presents a method of predicting zero shear viscosity (ZSV) on the basis of Van der Poel's nomograph. ZSV is a parameter describing pavement resistance to permanent deformation at high temperatures. An approximate ZSV evaluation using the presented method can lower the number and cost of tests required to select asphalt for a specific asphaltic mixture.

2. Identification of asphalt rheological properties

The paving asphalt is a visco-elastic material under typical operational conditions. Asphalt stiffness depends on the temperature and load time, while its rheological properties depend on its composition (Trzaska 2012). The classification into rheological types by composition is presented in Table 1. The optimal rheological type for paving asphalts is sol-gel (Radziszewski et al. 2014).

Table 1. Rheological types of asphalt based on the chemical composition (Trzaska 2012).

Rheological type of asphalt	Mass content of components [%]		
	asphaltenes	resins	oils
gel	> 25	< 24	> 50
sol	< 18	> 36	< 40
sol-gel	20-23	30-40	45-50

Changes in mechanical properties under the influence of temperature significantly depend on intermolecular interactions, such as the electrostatic force and other short range forces. These are weak interactions that allow molecules to organize into bigger structures. An organized structure can be destroyed by physical stress or increasing its temperature. More organized structures are less vulnerable to deformations, thus asphalt shows higher stiffness and viscosity at lower temperatures. This is a very complex phenomenon. Rheological models have many capabilities for describing the mechanical properties of asphalts, but they usually require labor-consuming research. The following article presents a method employing Burger's viscoelastic rheological model for paving asphalts using Van der Poel's nomograph. This method is an adaptation of the method proposed by Zbiciak et al. (2015) for asphalt-aggregate mixtures.

Asphalt stiffness can be estimated at a constant temperature with different load times. It is possible to use the Eq. 1, which is a strict analytical solution of Burger's creep test (Nowacki 1963) in comparison with the obtained Van der Poel module (E_p).

$$\frac{1}{E_p(\Delta t)} = \frac{1}{E_1} + \frac{1}{\eta_1}\Delta t + \frac{1}{E_2}\left[1 - \exp\left(-\frac{E_2}{\eta_2}\Delta t\right)\right] \tag{1}$$

Where E_1, E_2, η_1 and η_2 represent material parameters. Using typical curve fitting procedures, the rheological model parameters can be determined. The calibrated rheological model can be used to simulate the material's response to various mechanical loads. The method requires multiple readings of the stiffness modulus from the nomograph; thus, a computer simulation of Van der Poel's nomograph was developed. There are other programs with a similar function (De Bats 1973), but advantage of our code is the open structure enabling facile adjustments to suit individual needs. A short program description, the source code in Mathematica® format and all information needed to use it are presented in the Appendix.

3. Zero shear viscosity estimation

ZSV is a material constant used as an asphaltic pavement rutting resistance indicator (Sybilski 1996). The following chapter presents the available literature results from two unmodified asphalts of different origins (Słowik and Andrzejczak 2014) and a computer simulation of the conducted tests.

3.1. Experimental data

The properties of two paving asphalts were analyzed. The asphalt from Venezuela was designated as V50/70 and the asphalt from Russia as R50/70. The results of the basic tests required to use the presented method are presented in Table 2.

Table 2. Basic properties of the tested asphalts.

Type of test	**Type of asphalt**	
	V50/70	**R50/70**
Penetration at 25°C [0.1 mm]	66.2	59.9
Softening point (TR&B) [°C]	55.0	49.2

The ZSV values were determined using two methods. The first method consists of applying the lowest possible static shearing stress that causes creep of the asphalt sample. It was assumed that, in the final loading stage (final 20% of the test time), the deformation growth is the result of the viscous flow of bitumen. Accordingly, the ZSV can be calculated from the following formula (Eq. 2):

$$ZSV = \frac{\Delta t}{\Delta J} = \frac{0.2 \cdot t_{TOT}}{J(t_{TOT}) - J(0.8 \cdot t_{TOT})} [Pa \cdot s] \tag{2}$$

where:
Δt – time change [s],
ΔJ – compliance change [1/Pa],
$J(t_{TOT})$ – compliance determined at time t_{TOT} [1/Pa],
t_{TOT} – total time of creep test [s].

An alternative method of calculating ZSV is dynamic loading in the form of sinusoidal angular deformation. Using a theoretical test solution for Burger's model and assuming that oscillation frequency tends to zero, ZSV can be determined from the following formula (Eq. 3):

$$ZSV = \eta_1 = \frac{|G^*|}{\omega \cdot \sin\delta} [Pa \cdot s] \tag{3}$$

where:
η_1 – material parameter from Burger's model [Pa·s],
$|G^*|$ – dynamic shearing modulus [Pa],
ω – oscillation frequency [rad/s],
δ – phase shift angle [rad].

Detailed description of conducted research is presented in literature (Słowik and Andrzejczak 2014).

3.2. Numerical estimation

A simulation of described material tests can be also conducted numerically, using Van der Poel's nomograph, i.e. the asphalt stiffness modulus can be estimated using the nomograph. The ZSV value was determined on the basis of shearing tests. The following formula (Eq. 4) was used to calculate the shearing modulus:

$$|G^*| = \frac{|E^*|}{2 \cdot (1+\upsilon)} [Pa] \tag{4}$$

where:

$|G^*|$ – dynamic shearing modulus [Pa],

$|E^*|$ – dynamic stiffness modulus [Pa],

υ – Poisson's ratio.

Poisson's ratio is dependent upon research conditions, e.g. load frequency (Allou et al. 2015). For the purposes of our analysis, a constant value was assumed, i.e. $\upsilon = 0.25$. Using the dynamic shearing modulus value obtained from Eq. 4 and Van der Poel's nomograph, material test simulations can be performed for every load time. Calculating ZSV using the creep test is very simple. The procedure only requires determining the value of the dynamic shearing modulus at two time points during the final load time stage. Then, the desired value can be obtained from Eq. 2, using the following equation 5 (Biro et al. 2009):

$$\Delta J = \frac{1}{|G^*|(t_{TOT})} - \frac{1}{|G^*|(0.8 \cdot t_{TOT})} [Pa \cdot s] \tag{5}$$

where:

ΔJ – compliance increment [1/Pa],

$|G^*|(t_{TOT})$ – dynamic shearing modulus determined in time t_{TOT} [Pa],

t_{TOT} – total time of creep test [s].

The simulation of the dynamic test requires Burger's rheological model parameters to be determined. These can be obtained using the method described by Zbiciak et al. (2015). The ZSV value matches one of the obtained parameter values (see Eq. 3). The method involves the calculation of the dynamic shearing modulus at different load times. With a large enough set of points (28 in this article), an artificial creep curve can be created. Using the analytical solution of Burger's model creep test (Eq. 1), the parameters should be set to match the curve with the obtained points.

3.3. Results

Both simulation methods, including the nomograph, were used to estimate the dynamic shearing modulus. On the basis of the obtained values, further calculations were conducted to compute the ZSV value. A comparison of the dynamic shearing moduli obtained from the tests and simulations are presented in Figures 1 and 2, whereas Figure 3 shows the results of determining ZSV by the different methods. The OSC abbreviation refers to tests with an oscillatory load while CREEP indicates the creep test. The suffix SYM indicates the results of the computer simulation.

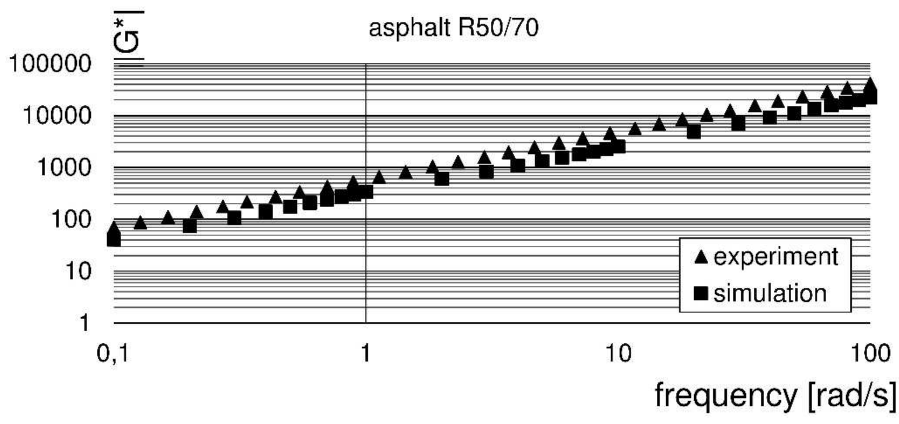

Fig. 1. Comparison of the shearing modulus results obtained from the tests and simulation for R50/70 asphalt.

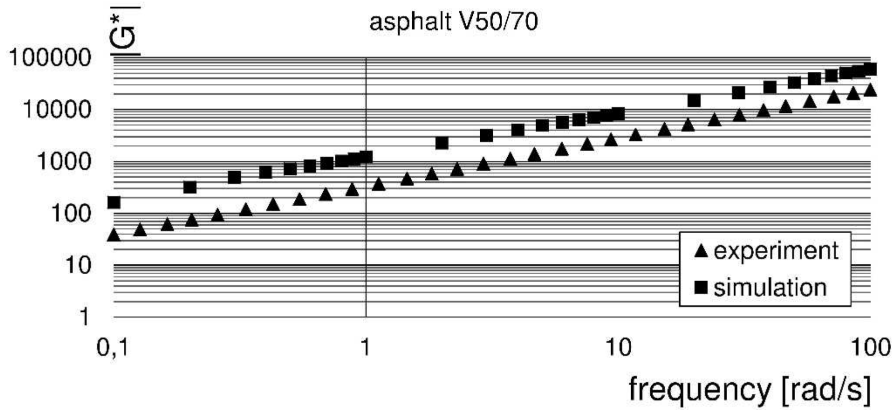

Fig. 2. Comparison of the shearing modulus results obtained from the tests and simulation for V50/70 asphalt.

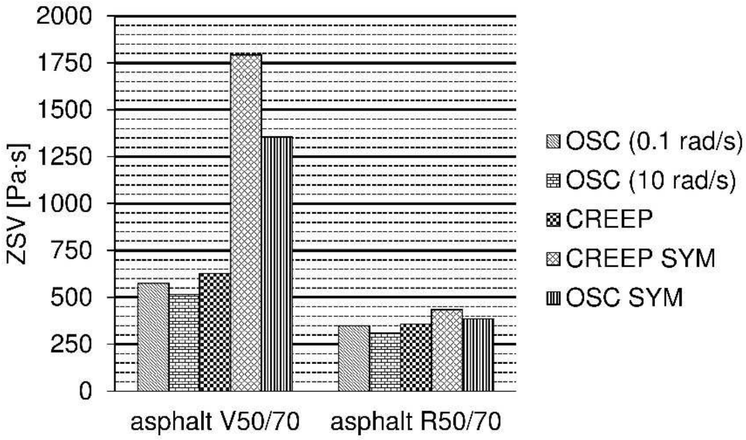

Fig. 3. Comparison of the ZSV results obtained with different methods.

The estimated dynamic shearing moduli of the Russian asphalt (R50/70) were slightly underestimated, but the values obtained from the simulation did not diverge significantly from the experimental results. This provided a good ZSV estimation, as can be observed in Figure 3. On the contrary, the shearing modulus estimation in the case of the Venezuelan asphalt (V50/70) diverged far more from the experimental results. Moreover, the ZSV values obtained via the simulation were greatly overestimated (about twice as high in the case of the dynamic test simulation and three-fold higher in the creep test simulation).

4. Conclusions

For the purposes of this study, three substantial steps have been made. The aim was to improve scientific analysis and research connected with the rheological properties asphalt.

- A computer simulation of Van der Poel's nomograph was programed,
- A method of identifying rheological model parameters introduced by Zbiciak et al. (2015) for asphaltic mixtures was adapted for asphalt,
- Example applications of the method were presented, which provided ZSV values using material test simulations.

The ZSV values obtained with the material test simulations were compared with results available in the literature for two different asphalts (Słowik and Andrzejczak 2014). The estimation carried out for the Russian asphalt (R50/70) agreed very well with previous experiments. However, the in case of the Venezuelan asphalt (V50/70), both the ZSV and dynamic shearing modulus estimations were overrated. The method is based on an approximation of asphalt stiffness using Van der Poel's nomograph. Thus, its accuracy is determined by the accuracy of the nomograph. The estimation showed imprecise accuracy for both asphalts, but it should be emphasized that it serves as a preliminary test of asphalt properties, and may reduce research time and cost.

Obtaining the ZSV at a particular temperature by applying this method requires only penetration and softening point values.

References

Allou F., Takarli M., Dubois F., Petit C., Absi J.: Numerical finite element formulation of the 3D linear viscoelastic material model: Complex Poisson's ratio of bituminous mixtures. Archives of Civil and Mechanical Engineering 15 (2015), 1138-1148. http://dx.doi.org/10.1016/j.acme.2015.02.003

Biro S., Gandhi T., Amirkhanian S.: Determination of zero shear viscosity of warm asphalt binder. Construction and Building Materials 23 (2009), 2080-2086. http://dx.doi.org/10.1016/j.conbuildmat.2008.08.015

De Bats F. Th.: A computer simulation of van der Poel's nomograph. Journal of Applied Chemistry and Biotechnology (1973), 139-140.

Di Mino G., Airey G., Di Paola M., Pinnola F. P., D'Angello G., Lo Presti D.: Linear and nonlinear fractional hereditary constitutive laws of asphalt mixtures. Journal of Civil Engineering and Management (2014 - in press). http://dx.doi.org/10.3846/13923730.2014.914104

Nowacki W.: Theory of creep (in Polish). Arkady, Warsaw, 1963.

Radziszewski P., Kowalski K. J., Król J. B., Sarnowski M., Piłat J.: Quality assessment of bituminous binder based on the viscoelastic properties: Polish experience. Journal of Civil Engineering and Management 20 (2014), 111-120. http://dx.doi.org/10.3846/13923730.2013.843586

Piłat J., Radziszewski P.: Asphalt pavements (in Polish). Transport and Communication Publishers, Warsaw, 2010.

Słowik M., Andrzejczak M.: Study of the zero shear viscosity of SBS copolymer modified bitumens (in Polish). Budownictwo i Architektura 13 (2014), 251-258.

Sybilski D.: Zero-Shear Viscosity of Bituminous Binder and Its Relation to Bituminous Mixture's Rutting Resistance. Transportation Research Record: Journal of the Transportation Research Board 1535 (1996), 15-21. http://dx.doi.org/10.3141/1535-03

Trzaska E.: The viscosity of bitumen and European methods of testing (in Polish). Nafta-Gaz 67 (2012), 446-453.

Trzaska E.: Paving bitumen – obtaining, classification and properties (in Polish). Nafta-Gaz 70 (2014), 325-335.

Zbiciak A., Brzeziński K., Michalczyk R.: Constitutive models of pavement asphaltic layers based on mixtures compositions. Journal of Civil Engineering and Management (in press, accepted in 2015). http://dx.doi.org/10.3846/13923730.2015.1128483

Zbiciak A.: Mathematical description of rheological properties of asphalt-aggregate mixes. Bulletin of the Polish Academy of Sciences: Technical Sciences 61 (2013), 65-72.

Appendix 1. Computer simulation of Van der Poel’s nomograph – code and description

Description

Van der Poel’s nomograph was set in a coordinate system and boundary lines were inserted between +1 and -2 as penetration index (PI) values, a typical range for paving asphalts. Then, every curve in the boundary was approximated with a function and a particular stiffness was attributed as follows. A certain number of points was set on every curve and their coordinates were transcribed to an external file. Thirty curves were approximated with a linear function (three points for each – two for determining coefficients, one for checking) and 14 curves were approximated with a third degree polynomial. Polynomial coefficients were obtained using the minimal square error method with 13 points for each curve. In total, there were 44 functions for stiffness between 10^{-8} Pa and $5{\cdot}10^{9}$ Pa.

The next step was to implement the input variables into the coordinate system. These included load time, penetration represented by the PI and temperature difference. Load time was estimated with a logarithmic function and temperature difference with a fourth degree polynomial. The coefficients were determined using the minimal square error method. A linear function going through two points representing the load time and temperature difference was created. The PI was approximated by a horizontal line, with the vertical position determined by the PI value. The intersection of both lines set the final point for the stiffness estimation. The algorithm checked the curve (function) on which the point was located and then estimated the stiffness value with a logarithmic formula.

Code in Mathematica® Language

```
(* The final function that allows to evaluate the asphalt stiffness from Van der Poel's Nomagraph is "stiffnessEvaluate[TRB_, pen25_, T_, t_]",
where:
TRB_ - softening point temperature, °C
pen25_ - penetration at 25°C
T_ - temperature of the asphalt, °C
t - time of the loading, s

Using this code requires the table of coefficients in CSV format (named "factorsTable.csv") to be placed in the same directory.*)
```

```
coordTime[t_] := {
  xTime = 14879.86 + 3260*Log10[t/10^(-6)];
  yTime = -31944.68;
  {xTime, yTime}
  };

coordTemp[dT_] := {
  xTemp =
   21396 + 82.066*dT + 0.5148*dT^2 + 0.0004*dT^3 - 6*10^(-6)*dT^4;   yTemp = -10452.019;
  {xTemp, yTemp}
  };

penIndex[TRB_,
  pen25_] := {pI = (20*TRB + 500*Log10[pen25] - 1952)/(TRB - 50*Log10[pen25] + 120);
  pI};

stiffCoord[TRB_, pen25_, T_, t_] := {
  yStiff = penIndex[TRB, pen25][[1]]*1000.;
  dT = TRB - T;
  coordTemp[dT];
  coordTime[t];
  factorA = (xTime - xTemp)/(yTime - yTemp);
  factorB = xTime - factorA*yTime;
  xStiff = factorA*yStiff + factorB;
  {xStiff, yStiff}
  };


stiffnessEvaluate[TRB_, pen25_, T_, t_] := {
    stiffCoord[TRB, pen25, T, t];
  factorTable = Import[NotebookDirectory[] <> "factorsTable.csv"];
  xMax = Sum[Last[factorTable][[k + 2]]*Power[yStiff, k], {k, 0, 3, 1}];
  If[xStiff >= 0 && yStiff >= -2000 && yStiff <= 1000 && xStiff <= xMax,
   {For[i = 3, i <= Length[factorTable], i++,
      {xLow = Sum[factorTable[[i - 1, k + 2]]*Power[yStiff, k], {k, 0, 3, 1}];
       xHigh = Sum[factorTable[[i, k + 2]]*Power[yStiff, k], {k, 0, 3, 1}];
       stiffLow = factorTable[[i - 1, 6]];
       stiffHigh = factorTable[[i, 6]];
       If[xLow == xStiff, stiffness = stiffLow];
       If[xHigh == xStiff, stiffness = stiffHigh];
       If[xLow < xStiff && xHigh > xStiff, {

         stiffness = stiffLow*10^((xStiff - xLow)* Log10[stiffHigh/stiffLow]/(xHigh - xLow));
         output = stiffness;}
        ];
        }];},
   output = "Data is out of range"];
  output};
```

factorsTable.csv

```
No,a0,a1,a2,a3,Stiffness [Pa]
1,-2437.992463,-1.801796231,0,0,0.00000001
2,-1867.886516,-2.045228258,0,0,0.0000001
3,-703.7106512,-2.083710326,0,0,0.000001
4,730.3548285,-2.039527586,0,0,0.00001
5,2256.263333,-1.947463333,0,0,0.0001
6,3896.33,-1.73403,0,0,0.001
7,4386.796667,-1.784846667,0,0,0.002
8,5122.713333,-1.685843333,0,0,0.005
9,5538.11,-1.6295,0,0,0.01
10,6018.766667,-1.603316667,0,0,0.02
11,6651.39,-1.54912,0,0,0.05
12,7170.543333,-1.504263333,0,0,0.1
13,7726.116667,-1.465496667,0,0,0.2
14,8300.736667,-1.378866667,0,0,0.5
```

15,8765.33,-1.33484,0,0,1
16,9263.366667,-1.318316667,0,0,2
17,9886.013333,-1.252733333,0,0,5
18,10351.11667,-1.206856667,0,0,10
19,10855.48,-1.15983,0,0,20
20,11582.06333,-1.048623333,0,0,50
21,12031.31,-0.99407,0,0,100
22,12591.53667,-0.940116667,0,0,200
23,13275.69667,-0.849976667,0,0,500
24,13733.56667,-0.847896667,0,0,1000
25,14375.66667,-0.748466667,0,0,2000
26,15092.89667,-0.672736667,0,0,5000
27,15622.18,-0.58069,0,0,10000
28,16217.23333,-0.471353333,0,0,20000
29,16916.6,-0.35676,0,0,50000
30,17387.32223,-0.244077211,4.26889E-05,3.69154E-09,100000
31,18018.18226,-0.133130609,2.92444E-05,-3.47301E-09,200000
32,18896.4306,0.021085476,5.22963E-05,5.34023E-09,500000
33,19486.57102,0.138917311,5.05778E-05,-6.63702E-09,1000000
34,20185.68347,0.263236999,8.34927E-05,1.26146E-08,2000000
35,21063.94751,0.489568646,0.000122671,1.54624E-08,5000000
36,21854.19232,0.746571029,0.000104663,-8.18126E-09,10000000
37,22590.02545,0.963911442,0.000165949,5.50788E-09,20000000
38,23862.94451,1.303289085,0.000241002,1.99056E-08,50000000
39,24987.67106,1.528246337,0.000171593,-9.66079E-09,100000000
40,26464.53105,2.192554276,0.000148891,-5.95368E-08,200000000
41,28400.21879,2.505434116,0.000125412,-2.63083E-08,500000000
42,30598.88092,3.139858866,9.53624E-05,-5.23877E-08,1000000000
43,34017.53512,3.282609239,4.77656E-05,-3.14269E-08,2500000000
44,36939.81,3.257,0,0,5000000000