How to Create the Best Suitable Map Projection

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Key words: map projection, best suitable projection, polyconic projection, composite projection, coordinate system, isocols (counters of equal distortions).

SUMMARY

This paper presents some drawbacks of the coordinate systems which currently are used in different countries. The Chebyshev-Grave criterion is used as the main criterion to develop the best suitable projection. The paper describes the methodology how to develop the best suitable projection based on polyconic and composite projection design. The principles and design for a map of isocols for a geodetic projection are presented here. Examples are given to analyze the character of the distortions in the best suitable projection for selected objects. In the paper we suggest that the best suitable projection could be used instead of a map projection library.

РЕЗЮМЕ

Данная работа отмечает некоторые недостатки существующих систем координат, которые используются в разных странах в настоящее время. Критерий Чебышева – Граве изложен как основной критерий развития наилучшей картографической проекции. Работа описывает методологию получения наилучшей картографической проекции на основе поликонических и композиционных проекций. Здесь также даны некоторые принципы построения карты изокол для геодезической проекции. Небольшой проект был рассмотрен для анализа характера искажений в наилучших проекциях для выбранных объектов. В работе также дана рекомендация по использованию алгоритма получения наилучшей проекции как альтернативы широкому классу картографических проекций.

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1. INTRODUCTION

Spatial information about the surface of Earth should be connected properly by a coordinate system. Any coordinate system can be used to determine the relative position within the survey area or in many cases to a much lager area. To support large engineering projects horizontal relations should be defined as two-dimensional on one (mapping) plane [Greenfeld, 2007]. Such coordinate system should be defined in a specific map projection.

There is a big amount of map projections nowadays, which used in order to carry out different projects. It is quite difficult to choose a suitable projection for a project. Each country has its own coordinate system in a specific projection. Very often the state coordinate system has to use a few coordinate zones to put the whole area of the country in it. Using state coordinate systems in this case is not so convenient because a user has to work with a few different coordinate systems. Large distortions are another drawback of state coordinate systems, because in most cases corrections have to be applied to distances and angles for surveying or cadastral purposes.

The idea of the best suitable projection is state-of-the-art for some countries. Several best projections have been proposed in the USA and Europe. In the USA the Transverse Mercator projection is used for 60 zones with a scale distortion of 0,9996 on the Central Meridian. The maximum distortions in this projection are 1/2500 [Greenfeld, 2007]. There are 5 different reference ellipsoids and 8 different cartographic projections in the EU countries. Annoni et al. [2001] stress that there are several drawbacks with the current coordinate systems and the projections they are based on. The problems are big distortions within the area of projection, bad connection between some coordinate systems and bad compatibility with GPS data.

Very often some counties or small regions of a country introduce their own or local coordinate system which is not properly connected with the state coordinate system. In a result of transformation of coordinates from the local system to the state system large distortions can occur.

This paper is written to show how to avoid the drawbacks of current coordinate systems. We propose the best suitable projection design for area and linear objects based on the theory of conformal representation. The paper is based on the previous work by Huryeu and Padshyvalau [2007] and Padshyvalau et al. [2005]. The idea of 'best suitable projection' design is based on the general algorithm of geodetic projections [Padshyvalau, 1998]. The main point of this paper is to compare our alternative to coordinate systems and map projections currently used in the world.

2. DEVELOPMENT OF THE BEST SUITABLE PROJECTION

2.1. Main criterion of the development best suitable projection

In cartography there are many map projections which more or less correspond to the idea of best suitable or "ideal" projection. Russian academic Chebyshev investigated this problem more carefully. His research resulted in the Chebyshev-Grave criterion [Mescheryakou, 1968] about the best suitable projection. The idea of this criterion is that isocol (counter of equal distortions) should coincide or be very close to a boundary of the represented area. In order to achieve this criterion we can take some special cases of geodetic projections (Gauss-Kruger cylindrical projection, Lambert conical projection, Russil stereographic projection) which were described by Padshyvalau et al. [2005]. Here we consider polyconic projections of Lagrange and composite projections which satisfied criterion of Chebishev-Grave.

2.2.Polyconic projection design

We can use the general form of formula [Padshyvalau et. al, 2005] for calculation of coordinates in polyconic projection:

$$
\begin{aligned}
x &= x_0 + \sum_{j=1}^{n} c_j P_j \\
y &= y_0 + \sum_{j=1}^{n} c_j Q_j \,.
\end{aligned}
\tag{2.1}
$$

Here x_0 and y_0 are the coordinates of the initial point of the projection. We assume that x_0 and y_0 can be set equal to the distance of the meridian arc and the ellipsoid parallel from the equator and the Greenwich meridian respectively, or to any fixed numerical value [Huryeu and Padshyvalau, 2007].
The P_j and Q_j are calculated from harmonic multinomial equations that satisfy to Laplace equations

$$
\begin{aligned}
P_j &= P_{j-1}P_1 - Q_{j-1}Q_1 \\
Q_j &= P_{j-1}Q_1 + Q_{j-1}P_1 ,
\end{aligned}
\tag{2.2}
$$

where $P_1 = \Delta q = q - q_0$ (q – isometric latitude of current point and q_0 – isometric latitude of central point in projection), $Q_1 = \Delta L = L - L_0$ (L – longitude of current point and L_0 – longitude of central point in projection), P_0=1, Q_0=0 and q can be expressed from the following equation given by Huryeu and Padshyvalau [2007].

Coefficients c_j up to the ninth degree for a polyconic projection have been derived:

$$\left.\begin{aligned}
&c_1 = m_0 \frac{c}{V_0}\cos B_0; \quad c_2 = \frac{c_1}{2}\alpha(1-2d); \quad c_3 = \frac{c_1}{6}\alpha^2(1-6d+6d^2);\\
&c_4 = \frac{c_1}{24}\alpha^3(1-14d+36d^2-24d^3);\\
&c_5 = \frac{c_1}{120}\alpha^4(1-30d+150d^2-240d^3+120d^4);\\
&c_6 = \frac{c_1}{720}\alpha^5(1-62d+540d^2-1560d^3+1800d^4-720d^5);\\
&c_7 = \frac{c_1}{5040}\alpha^6(1-126d+1806d^2-8400d^3+16800d^4-15120d^5+5040d^6);\\
&c_8 = \frac{c_1}{40320}\alpha^7(1-254d+5796d^2-40824d^3+126000d^4-191520d^5+141120d^6-\\
&-40320d^7);\\
&c_9 = \frac{c_1}{362880}\alpha^8(1-510d+18150d^2-186480d^3+834120d^4-1905120d^5+\\
&+2328480d^6-1451520d^7+362880d^8).
\end{aligned}\right\} \quad (2.3)$$

Here B_0 – latitude of a central point in projection, m_0 – scale of distortion in a central point of projection, $V_0 = \sqrt{1+e'^2\cos^2 B_0}$ and $d = \dfrac{\alpha+\sin B_0}{2\alpha}$, where $\alpha = \sqrt{1+\dfrac{1-(b/a)^2}{1+(b/a)^2}\cos^2 B_0}$.

As we can see the parameter α defines the coefficients c_j and depends on semi axes *a* and *b* of the ellipse with the best fit to the represented area. In order to get the best suitable projection based on polyconic projection we need to know the center of the assumed projection and the semi axes *a* and *b*.

Often we have to deal with raster maps in digital format. In order to define a polyconic projection for any chosen territory let us assume some arbitrary area (figure 2-1). By the algorithm we could define pixel's coordinates of counter represented area in the figure 2-1. From the set of counter points' coordinates we can choose maximum and minimum coordinates in the direction of West-East and North-South. By these extreme coordinates of the represented area it is easy to calculate a centre of ellipse which will be a centre of projection as well and semi axes *a* and *b* of this ellipse.

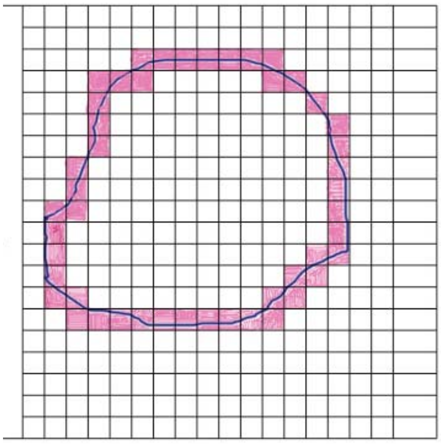

Figure 2-1: Arbitrary area representation

2.3. Composite projection design

The general principles of composite projection design were presented by Huryeu and Padshyvalau [2007].

Consider the general equation for the calculation of coordinates given by Huryeu and Padshyvalau [2007]

$$
\begin{aligned}
X &= k_1 X_1 + k_2 X_2 \\
Y &= k_1 Y_1 + k_2 Y_2 ,
\end{aligned}
\tag{2.3}
$$

where k_1 and k_2 are the coefficients of the cylindrical and the conical projections respectively while X_1, X_2, Y_1, Y_2 – coordinates of projections that formed the composite projection.

Here we consider an idea how to get the best suitable projection automatically. We consider an example with Netherlands (figure 2-2) to show a consequence of the algorithm. First we have to choose four points with extreme coordinates in the directions of North-South and West-East. In figure 2-2 there are four points: N (North), S (South), W (West) and E (East).

Figure 2-2: The Netherlands

Determine the geographical coordinates of the extreme points of the Netherlands (table 2-1).

Table 2-1: Geographical coordinates of extreme points for Netherlands

Point ID	B	L
N	$53^0 27'$	$6^0 49'$
S	$50^0 45'$	$6^0 02'$
W	$51^0 23'$	$3^0 23'$
E	$53^0 12'$	$7^0 14'$

The coordinates given in table 2-1 are input to the program for best suitable projection design. We have to define coefficients k_1, k_2 and the coordinates of the central point of projection B_0, L_0 to get a composite projection based on cylindrical and conical projections.

In order to reduce the execution time of the algorithm we set $k_1 = k_2 = 0{,}5$ and calculate the coordinates of the central point using the following formulas

$$B_0 = \frac{B_N + B_S}{2};\ L_0 = \frac{L_W + L_E}{2},$$

where B_N and B_S are latitudes of points North and South accordingly; L_W and L_E are longitudes of points West and East accordingly.

We obtain preliminary rectangular coordinates for these points and the numerical characteristics γ - the Meridian Convergence and m - the scale of distortion (table 2-2).

Table 2-2: Preliminary coordinates of the boundary points and their numeric characteristics

Point ID	X, m	Y, m	m	γ, ⁰
N	5925850,8700	99666,0573	1,00020	1,1943645
S	5624613,5409	50585,4382	1,00015	0,5602523
W	5696614,5401	-134590,8561	1,00015	-1,5181876
E	5898688,4608	128087,4679	1,00019	1,5236767

We wish to get the desired result is that in all four points the scale of distortion *m* will be equal within of specified accuracy. In order to get the best suitable projection for the Netherlands we need to do the following:

1) change coefficients k_1 and k_2 until $m_S = m_N$;
2) change B_0 until $m_N = m_S$;
3) change L_0 until $m_W = m_E$.

Steps 1-3 should be repeated until $m_N = m_S = m_W = m_E$. When this condition is fulfilled the counter of equal distortions (best fitted ellipse) passes through all four points.

In our example we changed these values until we got the best suitable projection with the parameters $k_1 = 0{,}514$, $k_2 = 0{,}486$ and $B_0 = 52^0 13'$, $L_0 = 5^0 22'$. The results of the final calculations are given in table 2-3.

Table 2-3. Coordinates of boundary points in the best suitable projection for the Netherlands

Point ID	X, m	Y, m	m	γ, ⁰
N	5925781,9152	96341,6691	1,00017	1,1557204
S	5624578,6594	47057,2383	1,00017	0,5214321
W	5696708,6470	-138072,8820	1,00017	-1,5584496
E	5898601,1353	124744,0922	1,00017	1,4853639

For all points in table 2-3 condition $m_N = m_S = m_W = m_E$ is true. This means the parameters of the new projection k_1, k_2, B_0, L_0 satisfies the Chebyshev-Grave criterion above.

3. ANALYS OF DISTORTIONS IN THE BEST SUITABLE PROJECTION BY A MAP OF ISOCOLS

3.1 Principles of design a map of isocols for a geodetic projection

Isocols (contours of equal distortions) define the distribution of distortions in a chosen projection. Here we consider the idea to design the map of isocols in general. Firstly, we have to define the extreme coordinates of an area (trapezium) which includes the represented object (figure 3-1). This area should be divided in to a certain number of nodes (in figure 3-1 there are 320 nodes). The quality of the map of isocols and the complexity of the calculations depend on the number of nodes. In order to design the map of isocols the scale of distortion *m* should be calculated for each node. There are two ways to calculate *m*.

Figure 3-1: Trapezium with represented area in it

The first way is based on the general algorithm of geodetic projections [Padshyvalau , 1998]. The scale of distortion at any point is calculated by the following formula:

$$m = \frac{\sqrt{t_1^2 + t_2^2}}{r_0}, \tag{3.1}$$

where $t_1 = -\sum_{j=1}^{n} jc_j Q_{(j-1)}$ and $t_2 = \sum_{j=1}^{n} jc_j P_{(j-1)}$; c_j – coefficients defining the type of projection; P_j and Q_j are calculated according formula (2.2); $r_0 = \frac{c}{V_0}\cos B_0$ - radius of the standard parallel; c – polar radius of the Earth’s curvature and $V_0 = \sqrt{1 + e'^2 \cos B_0}$ - latitude function of the central point.

The coefficients c_j for the polyconic projection are given in section 2.2 above in this paper and for cylindrical and conic projection by Padshyvalau et al. [2005]. For the composite projection write the following formula:

$$c_j = k_1 c_j^I + k_2 c_j^{II} \tag{3.2}$$

Here c_j^I and c_j^{II} are coefficients which are defined by the first and the second projection in the composite projection.

The second way to calculate *m* is based on an approximation formula for the scale of distortions:

$$m = m_0 + \frac{k_1 \Delta X^2 + k_2 \Delta Y^2}{2 m_0 R_0^2}. \tag{3.3}$$

Here m_0 - the scale of distortion in the central point of the projection; k_1 - the coefficient of the participating conical projection; k_2 - the coefficient of the participating cylindrical projection. If k_1 and k_2 are positive then isocols will be presented by ellipses. If one of the coefficients is negative then isocols will be presented by hyperboles.

The increments ΔX and ΔY are defined by the coordinates of a point (X, Y) on a map raster: $\Delta X = X - X_0$; $\Delta Y = Y - Y_0$.
If we set $X_0 = 0$ and $Y_0 = 0$ for the equations of the increments we can rewrite formula (3.3) as

$$m = m_0 + \frac{k_1 X^2 + k_2 Y^2}{2 m_0 R_0^2}, \tag{3.4}$$

where $R_0 = \dfrac{c}{V_0}$ - median radius of curvature in central point of projection.

After the calculation of *m* for all nodes by formula (3.1) or (3.3) for the defined area we can design the map of isocols by interpolation methods.

3.2. The maps of isocols for the examples

In order to consider how the methodology above works we present the example below. For the example we have chosen the area of Germany and the Netherlands (figure 3-2). For this area we design the best projection using polyconic and composite projections. We also consider the design of the best suitable projection for two linear objects (highways Rotterdam – Munich and Amsterdam – Berlin) which cross the territory of Germany and the Netherlands.

Figure 3-2: Map of case study

Consider the following order to design the polyconic projection for the case study. We have chosen four points N (North), S (South), W (West) and E (East) to define the boundary of the area (figure 3-2). The coordinates of the points are presented in table 1 of the Appendix (columns B and L). Then we have calculated the center of the projection and the semi axes of the ellipse which best fits the study area according to the theory given in section 2 of this paper. Parameter α, coordinates X, Y and numeric characteristics m and γ are given in table 1 of the Appendix.

For this area we also design a best suitable projection using a composite projection. The parameters k_1, k_2 and B_0, L_0 for the composite projection are derived in an automated way by the algorithm presented in section 2. The results of the calculation of the coordinates and the numeric characteristics are given in table 2 of the Appendix.

In order to show the character of the distortion in this composite projection we have drawn the map of isocols which is shown in figure 3-3.

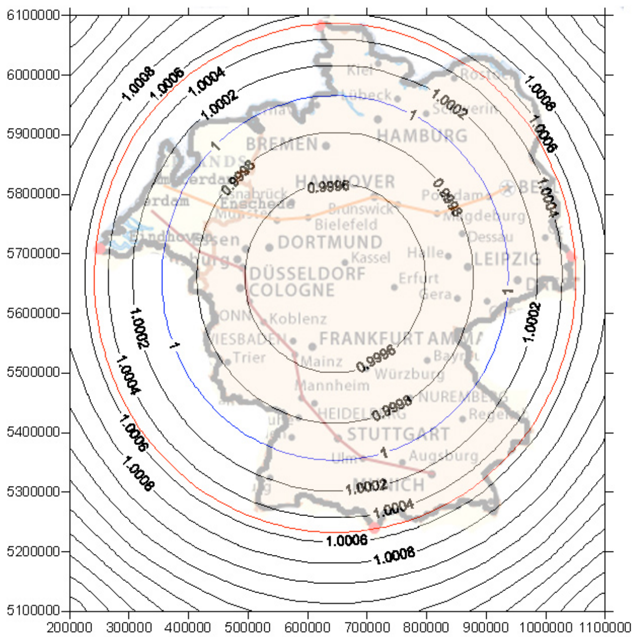

Figure 3-3: Map of isocols for area of Germany and Netherlands in best suitable projection

We also have developed the best suitable projections for the highways Amsterdam – Berlin and Rotterdam – Munich. In order to get the best suitable projections for these objects we have used the principles given by Huryeu and Padshyvalau [2007]. First we need to have a set of geographic coordinates for points of a linear object as necessary data to design the best suitable projection. For our highways Amsterdam – Berlin and Rotterdam – Munich the geographical coordinates are given in tables 3 and 4 of the Appendix (columns B and L). Coefficients k_1 and k_2 for the cylindrical and the conical projections are defined by line of regression for the set of points. Coordinates X, Y and some numerical characteristics of the best suitable projection for the roads are given in table 3 and 4 of the Appendix.

Figures 3-4 and 3-5 presents the maps of isocols for the highways Amsterdam – Berlin and Rotterdam – Munich .

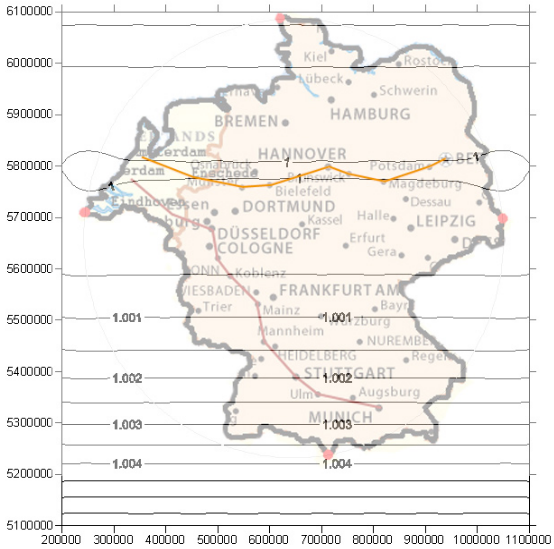

Figure 3-4: Map of isocols for the highway Amsterdam – Berlin.

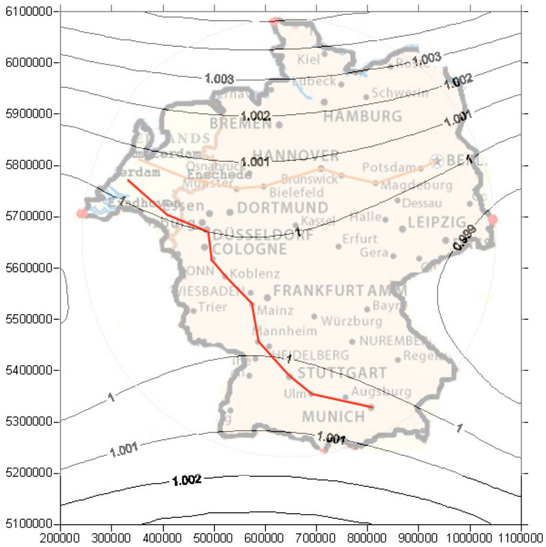

Figure 3-5: Map of isocols for the highway Rotterdam - Munich

3.3. Discussion and analysis of distortions for the case study

Nowadays for Germany the Transverse Mercator (UTM) projection is used and for the Netherlands the Oblique Stereographic projection is used. The territory of Germany is located in three 6^0 zones with maximum distortions equal of 1/2500 in UTM and 1/1250 in Gauss-Kruger projection. The territory of the Netherlands is in stereographic projection which is different from UTM. In the best suitable projection above the territory of Germany and the Netherlands are represented with distortions less than 1/2000. As we can see in figure 3-3 about 30% of the territory is represented with distortions less than 1/5000 and about 90% of the area has distortions less than 1/2500. Only negligible part of the territory has distortions about 1/2000.

In figure 3-4 the highway Amsterdam – Berlin has negligible distortions because the object is located along the parallel. As we can see for the whole object the distortions are less than 1/185000. The maximum distortion occurs for point Munster and that amounts to 1.000005 (Table 3 of the Appendix). For the other linear object, Rotterdam - Munich in figure 3-5, the distortions in some points get to 1/4100. The maximum distortions occur for points Mannheim and Munich and that amount to 0.999756 and 1.000243 respectively (table 4 of the Appendix). The character of distortions in projection for linear objects depends on location of the object.

Through the map of isocols we can see the character of the distortions in any composite projection. The scale of distortion for any point with known coordinates can be calculated by the formula presented in section 3.1. By varying the scale m_0 in the central point of the projection it is possible to reduce the distortions for a specific area within the territory considered.

4. CONCLUSIONS

In this paper we discussed the principles of the best suitable projection design on the basis of polyconic and composite projections for different types of objects. We assume that our algorithm could be utilized in any software where map projections are used. Our algorithm can be used as an alternative to known map projections. The methodology above has several advantages. Firstly, we use only one general equation for the calculation of coordinates (2.1) in which we define the class of the projection by coefficients c_j. Secondly, there are no problems in the transformation between coordinate systems described by the general algorithm [Padshyvalau, 1998]. Thirdly, it is possible to obtain a coordinate system using the best suitable projection design connected to the state coordinate system for any small area or object with very high accuracy of representation instead of applying local or assumed coordinate system. It is also possible to manage the character of the distortions in a projection by the map of isocols.

The theory presented here can be applied to territories that do not exceed 16^0 in longitude and latitude with an accuracy of calculation 0,001 m for lengths and 0,001" for angles. In GIS applications it is often needed to work with large areas. Using the methodology above for areas larger than 16^0x16^0 is possible, but the accuracy of calculation will decrease. As we can see in our examples there is no need to represent territory of Germany in three 6^0 zones, which is not convenient for the user. It might be a good idea to use such coordinate systems for building and to support different types of linear objects (railway roads, highway roads, gas pipelines and etc.) in GIS.

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BIOGRAPHICAL NOTES

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APPENDIX

Table 1:Polyconic projection design for Germany and the Netherlands with parameters of projection $B_0=51^0 04'$, $L_0=9^0 13'$, $\alpha=1{,}0095$, $m_0=0{,}99945$

ID Point	B	L	X, m	Y, m	m	$\gamma, ^0$	$\left(\frac{\partial S}{S}\right)_{max}$
N	$54^0 54'$	$8^0 39'$	6086265.1498	609699.3047	1.000522	-0.453262	1/1900
S	$47^0 14'$	$10^0 13'$	5233862.2252	721835.1436	1.000552	0.755906	1/1800
W	$51^0 23'$	$3^0 23'$	5710926.0426	240464.7623	1.000522	-4.549827	1/1900
E	$51^0 17'$	$15^0 03'$	5699829.6389	1052561.4142	1.000521	4.546485	1/1900

Table 2. Composite projection design for Germany and theNetherlands with parameters of projection $B_0=51^0 04'$, $L_0=9^0 13'$, $k_1=0{,}525$, $k_2=0{,}475$, $m_0=0{,}99945$

ID Point	B	L	X, m	Y, m	m	$\gamma, ^0$	$\left(\frac{\partial S}{S}\right)_{max}$
N	$54^0 54'$	$8^0 39'$	6086268.0402	609698.1888	1.000552	-0.4527679	1/1800
S	$47^0 14'$	$10^0 13'$	5233865.4599	721832.6253	1.000521	0.7549487	1/1900
W	$51^0 23'$	$3^0 23'$	5710928.9501	240465.4027	1.000519	-4.5514800	1/1900
E	$51^0 17'$	$15^0 03'$	5699832.5988	1052561.0929	1.000520	4.5481471	1/1900

Table 3. Composite projection design for the highway Amsterdam – Berlin with parameters of projection $B_0=52^0 15'$, $L_0=9^0 9'$, $k_1=-0{,}0008$, $k_2=1{,}0008$, $m_0=0{,}999995$

ID Point	B	L	X, m	Y, m	m	$\gamma, ^0$	$\left(\frac{\partial S}{S}\right)_{max}$
Amsterdam	$52^0 22'$	$4^0 53'$	5812798.4616	334445.5955	0.999997	-3.37361	1/300300
Enchede	$52^0 13'$	$6^0 53'$	5789976.3308	470013.6405	0.999995	-1.79223	1/191200
Munster	$51^0 59'$	$10^0 05'$	5762003.2954	689030.5655	1.000005	0.737977	1/185800
Bielefeld	$52^0 01'$	$8^0 32'$	5765479.4666	582571.6157	1.000003	-0.48759	1/350000
Hannover	$52^0 22'$	$9^0 44'$	5804404.6353	664641.7775	0.999997	0.461236	1/299000
Braunschweig	$52^0 16'$	$10^0 32'$	5794018.6412	719342.0119	0.999995	1.093787	1/183700
Magdeburg	$52^0 08'$	$11^0 38'$	5781194.3678	794919.8619	0.999997	1.963546	1/276600
Potsdam	$52^0 24'$	$13^0 07'$	5815341.8188	894764.8118	0.999998	3.136402	1/372000
Berlin	$52^0 13'$	$13^0 25'$	5829461.1564	1539295.0122	1.000005	3.373597	1/216700

Table 4. Composite projection design for the highway Rotterdam – Munich with parameters of projection $B_0=50^0 02'$, $L_0=8^0 02'$, $k_1= -0{,}47424$, $k_2=1{,}47424$, $m_0=0{,}999757$

ID Point	B	L	X, m	Y, m	m	$\gamma, ^0$	$\left(\frac{\partial S}{S}\right)_{max}$
Rotterdam	$51^0 55'$	$4^0 28'$	5759957.2440	330138.2667	1.000212	-2.69788	1/4700
Eindhoven	$51^0 26'$	$5^0 29'$	5703375.7229	398241.6753	1.000017	-1.93542	1/57100
Dusseldorf	$51^0 13'$	$6^0 47'$	5676995.8294	488226.8097	1.000029	-0.95023	1/34700
Bonn	$50^0 42'$	$7^0 07'$	5619190.4666	510815.5322	0.999833	-0.69931	1/6000
Koblenz	$50^0 21'$	$7^0 36'$	5579957.3621	544731.6395	0.999774	-0.33139	1/4400
Mannheim	$49^0 29'$	$8^0 27'$	5539111.1621	589907.9968	0.999756	0.153337	1/4100
Stuttgart	$48^0 47'$	$9^0 11'$	5483575.6498	605754.2906	0.999819	0.320565	1/5500
Ulm	$48^0 23'$	$9^0 57'$	5406301.2139	660084.7248	1.000062	0.889097	1/16000
Munich	$48^0 08'$	$11^0 35'$	5362995.4780	717568.2396	1.000243	1.485952	1/4100