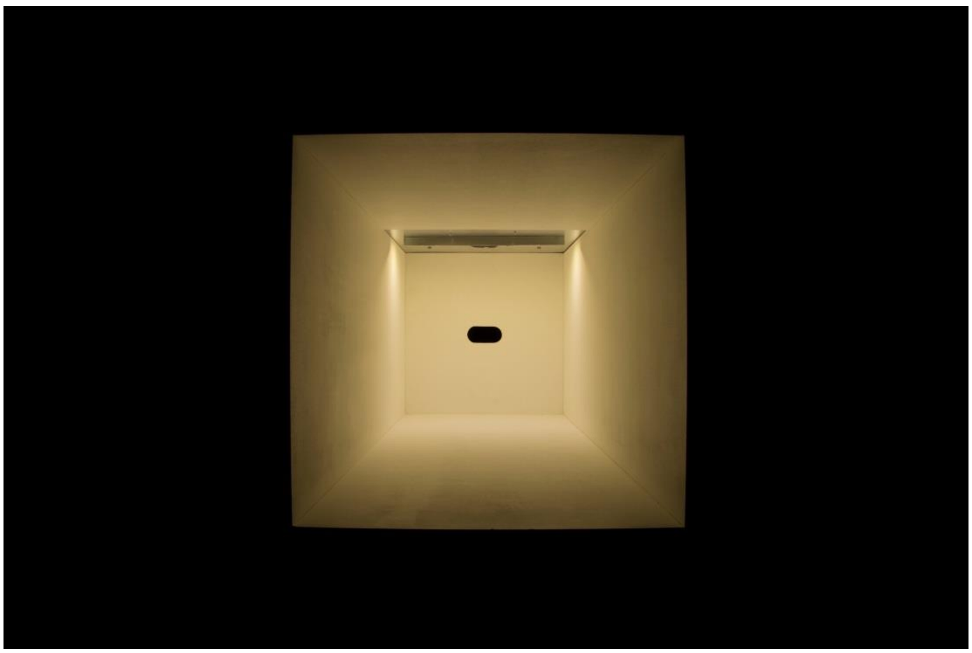
Research Project: Visual adaptation for tunnel entrance

Final report, November 2013



Commissioned by TRAFIKVERKET

Eran Aronson MSc, Researcher

Lighting Laboratory

KTH STH

School of Technology and Health

Contents

Abstract

Background: The research presented here is in fact part of an ongoing program to study tunnel lighting and the ways to improve it. Preceding this part of the research, which is focusing on the tunnel entrance zones, is a research focused on the interior zone of tunnels. We have been concentrating our efforts, in this part of the research, on establishing a hypothesis while testing with a scale model before continuing tests in the future, possibly at full scale. Our main objective is to establish a basis for future research by answering the following questions: *What is the length of time needed for a driver to adapt form exterior luminance levels to interior luminance levels, while recognizing an obstacle in the tunnel? And, what is the light level needed inside a tunnel for a driver to recognize an obstacle from the exterior?*

Data: We have 128 valid tests and at two different light levels; 8000cd/m^2 and 6000cd/m^2.
Within these two categories we have tests only for adaptation (time) and combined tests for adaptation and recognition (levels/K factor) at the same sequence.
At 8000cd/m^2 we have 53 tests with 10 combined tests and 43 with time alone.
At 6000cd/m^2 we have 75 tests with 46 combined tests and 29 with time alone.
That is 56 combined tests and 72 tests with time alone for both light levels= 128 in Total.

Results: Our results show two main indications: **1.** Time needed for recognition is shorter in our tests then indicated in the current technical specifications. **2.** Age has an immediate effect on the test results. In statistical terms; there is a correlation between age and adaptation time.

Overview

Personnel involved:

KTH	**Trafikverket**
Eran Aronson, M.Sc. Researcher.	Henrik Gidlund, Project manager.
Prof. Jan Ejhed, Supervisor.	Petter Hafdell, Project advisor.
Dr. Elias Said, Statistics analysis	
Dr. Thomas Müller, report review.	

The research process, from beginning up to this stage, was structured as follows:

- **November-December 2012**, formulating the objectives and planning the methodology.
- **January-February 2013**, constructing the scale tunnel model and conducting first tests.
- **March-June 2013**, conducting series of tests, accumulating data, improving the test sequence and holding seminars on the subject in Stockholm, Gothenburg and Helsinki.
- **August-September 2013**, analyzing raw data to formulate figures and graphs according to methodology.
- **October-December 2013,** formulating a report for the complete process.

Key terminology (From CIE88:2004, 2nd edition):

***Lseq* Equivalent veiling luminance**: the light veil as a result of the ocular scatter, Lseq is quantified as luminance.

***Lth* Threshold zone luminance** (at a specific location in the threshold zone): the average road surface luminance at that location.

***Ltr* Transition zone luminance** (at a particular location): the average road surface luminance in a transverse section at the particular location in the transition zone of the tunnel.

***Lin* Interior zone luminance** (at any location in the interior zone of the tunnel): the average road surface luminance at that location.

Introduction

The tunnel entrance is a zone where searching for improvements in lighting can become more complex than other zones of the tunnel, such as the interior zone. Besides the strong impact of entering a tunnel in general and as drivers at high speeds in particular do, we now physically confront a dramatic transition from daylight to low light levels in a matter of seconds. That combines together aspects related to psychology, photometry, the visual system and technology.

Reading through the current technical specifications by the CIE *(Guide for the Lighting of Road Tunnels and Underpasses, CIE 088-2004, ISBN 978 3 901906 31 2) and by the Swedish Road Administration – Trafikverket (Krav för vägars och gators utformning Trafikverkets dokumentbeteckning: TRVK Vägars och gators utformning, Publikationsnummer 2012:179, ISBN: 978-91-7467-383-8)*, we can extract the data which is the basic platform we use for comparison to our research and in a way acts partially as a motivator to our research. We are dealing with two main aspects of tunnel entrance lighting which are derived from basic driving visual tasks: Adaptation and recognition.

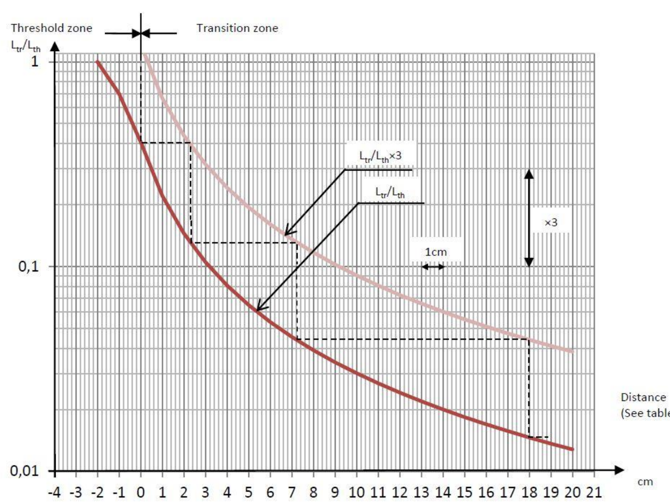


Fig.1

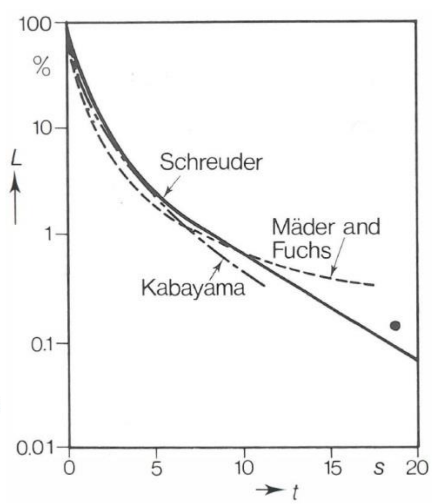


Fig.2

The two diagrams above demonstrate the common understandings for the adaptation curve as it is approached today. *Fig.1* on the left is taken from *Krav för vägars och gators utformning* and it displays the recommendation for the adaptation and dynamic recognition curve on entering a tunnel, where 1cm=1second. *Fig.2* on the right displays the adaptation curves by three different researches done in the 1960's, but not in use today. It is clear to see how they share a very similar curve to each other and to the modern standard shown on the left (*Fig.1*). From these diagrams we can conclude that a period of 20 seconds is considered as an acceptable time for visual adaptation from the tunnel entrance at the threshold zone (L_{th}), through the transition zone (L_{tr}) and into the interior zone (L_{in}) during daytime, i.e. from high daylight light levels to low interior light levels.

Connected directly to the adaptation curve are the recognition conditions. In order to formulate a diagram for the adaptation curve a set of parameters must be fixed, when one of them is regarding the obstacle to recognize. The curve showed here (Fig.1) responds to the condition that a specific obstacle is visible to the driver throughout the process of adaptation. That is the "*K*" factor, which is in fact the relation between light levels within a tunnel to those of the exterior. In other words; how much light is needed inside the tunnel and beyond the tunnel entrance portal in order for a user/driver to recognize it from the outside?

Hastighet	Tröskelzonens längd [a)]	$k = L_{th}/L_{20}$
40 km/tim	26 m	0,04
50 km/tim	38 m	0,04
60 km/tim	54 m	0,05
70 km/tim	75 m	0,05
80 km/tim	99 m	0,06
90 km/tim	125 m	0,06
100 km/tim	155 m	0,07
110 km/tim	187 m	0,07
120 km/tim	222 m	0,08

Fig.3

In the chart above, also taken from *Krav för vägars och gators utformning*, this relation is shown in a scale according to the design speed and the length of the threshold zone, which correlates to the stopping distance.

Therefore, the curves shown in figures 1 and 2 are actually the graphical demonstration of the *K-factor* parameter in motion; they are showing the condition of recognizing an obstacle while adapting to low light levels in a tunnel. Adaptation is dependent on recognition and these are the two core topics of this research.

Research questions

Our main aim of investigation is regarding the visual adaptation curve of a driver entering a tunnel. That focuses on two main questions:

- **What level of luminance is needed inside a tunnel for the approaching driver at the exterior to recognize an obstacle within the tunnel?**
- **How long does it take for a driver to adapt from a high exterior level of luminance to a low interior level of luminance, given the condition that an obstacle is seen in the tunnel throughout the process?**

Hypothesis

Adaptation time, for a driver transiting from high light levels at exterior of tunnel and into low light levels into the interior of a tunnel, is in fact shorter than suggested in the current technical specifications. We attempt to conduct practical tests in order for us to validate or disproof this hypothesis.

Expected results

Our initial expectations, regarding the adaptation curve, were predicting a substantial reduction in the adaptation time. That estimation came from some preliminary tests we conducted on ourselves at the lighting lab at KTH, and from consulting with experts that had backed the general idea. For the *K-factor* we haven't set a specific prediction.

Methodology

We have built a scale tunnel model at 1:100 to resemble what would be the visual tasks a driver will confront when driving along the access zone towards the tunnel entrance and into the threshold zone. This model is built following the CIE technical specifications, meaning that we use the dimensions at scale: for stopping distances 2meters (as 200 meters). The middle partition's width corresponds to a 20^0 angle of driver's peripheral view and the hole in that partition corresponds to a 2^0 angle for the target view as the foveal view. A 2x2x2mm cubic target to resemble a 200mm cubic target with 20% contrast (lighter) to the background. That background stands for the area after the entrance portal – which is at the beginning of the threshold zone.

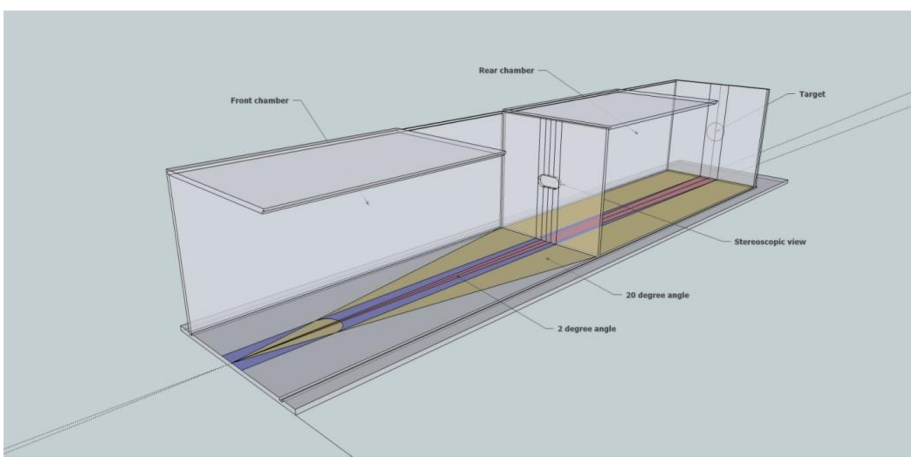


Fig.4

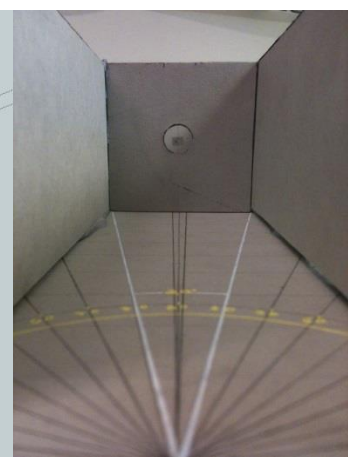


Fig.5

Testing methodology

- Both tests, recognition and adaptation if done separately or as one sequence, must proceed first with an adaptation time of 2 minutes to the highest light level for the specific chosen light level before proceeding with the test sequence.

- Although 2 meters represent 200 meters in reality, we test for a design speed of 100km/h which is 155 meters of stopping distance. That gap of 45 meters comes since our scale obstacle is “pushed” in the tunnel for this missing distance. That means that the imaginary entrance portal is at the last ¼ of the model.

1. **“K” factor: Test to measure the visual relation (in perception) between a daylight situation to the threshold lighting situation (Stages A+B).** This test is designed to check the light levels required for recognition of an obstacle within the threshold zone. Once the test subject is adapted to the high light levels within the front chamber (6000cd/m^2 or 8000cd/m^2), the light in the back chamber is turned up to a level where the test subject can clearly recognize the obstacle (2x2x2mm). This level we call *“Level 1”.* Next, the light in the back chamber is dimmed down until the test subject indicates that he/she cannot be certain of recognizing the target anymore. This is *“Level 2”* and its purpose is for us to get scaling proportions as a reference to Level 1, which is actually the data we seek
2. **Test to measure the adaptation time when shifting from daylight conditions to the minimum of tunnel lighting levels within the Interior zone (Stages C+D).** In the front chamber we will emit light at a level of 6000cd/m^2 or 8000cd/m^2, measured on the middle partition. Once the participant is visually fully adjusted, we will lower the light level in the front chamber to 2cd/m^2 in one rapid act and measure the time until he/she can fully recognize the target in the back chamber where light levels are at 2cd/m^2. This test will give us a firm assessment of the actual average time needed for our visual system to adjust from daylight (L_{seq} at the access zone) to minimal tunnel lighting conditions (L_{in} at the interior zone).

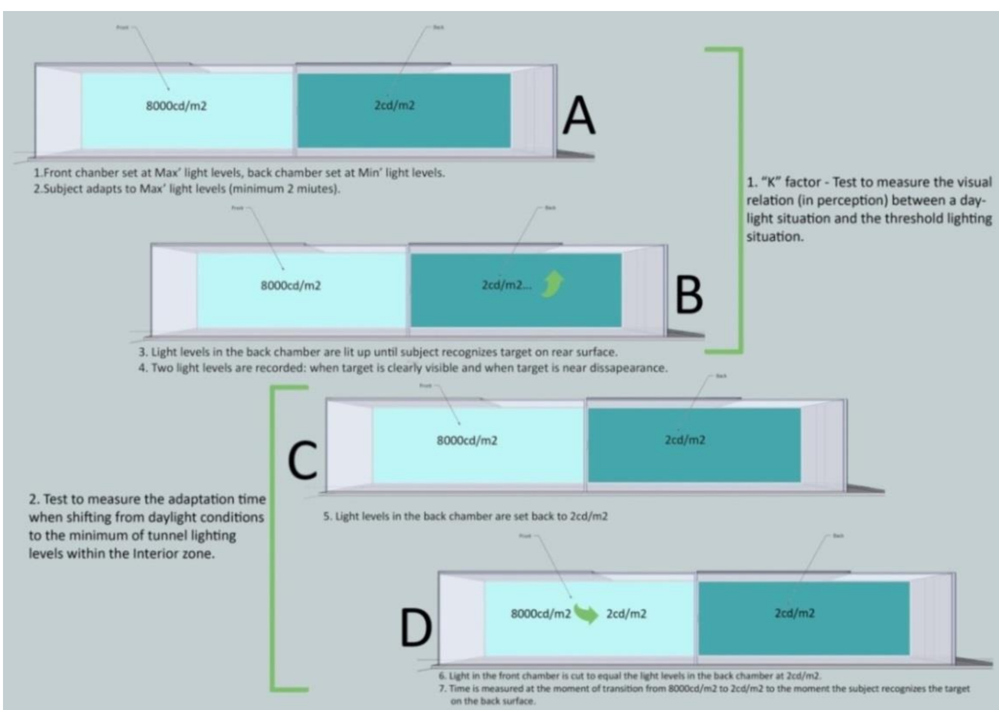


Fig.6. Testing sequence

Testing

Testing took place during 8 different occasions. Having the scale model built as a collapsible structure, we could easily transport it around Sweden and on one occasion to Finland. The table below displays the testing chronology between February 2013 and July 2013.

Date	Location	Type	Participants
2013/02/05-09	Stockholm light and furniture fair, Älvsjo	Adaptation only	41 at 8000cd/m^2 29 at 6000cd/m^2
2013/04/17	Radisson Blu Stockholm, Trafikverket conference	Adaptation and levels	8 at 8000cd/m^2
2013/04/24	Majvik Finland, Scandinavian lighting engineers conference	Adaptation and levels	6 at 8000cd/m^2
2013/05/7	Trfikverket Solna, Specialists conference	Adaptation and levels	8 at 6000cd/m^2
2013/05/16	Elfack tradefair, Gothenburg	Adaptation and levels	9 at 6000cd/m^2
2013/05/22	Radisson Blu Royal Park Hotel Solna, Trafikverket conference	Adaptation and levels	12 at 6000cd/m^2
2013/06/03	KTH campus Handen, academic staff	Adaptation and levels	14 at 6000cd/m^2
2013/07/09	KTH campus Handen, specialist seminar	Adaptation and levels	3 at 6000cd/m^2

- The sum of all participants adds to 130 according to the table above. In fact we count 128 participants since 2 tests were deleted due to extreme time measurements that we consider as faulty.
- Age of participants varied from 20 to 76. Detailed information is presented in the results chapter.
- All participants are drivers by definition, meaning that they have a driver's license and that they are active drivers.
- Participants who wear optical lenses when driving were requested to wear them while taking the test.
- Besides the relevant technical data regarding the participants (age, gender, optics), we did not record any other information about the test participants such as socioeconomic, ethnicity, education and so on. There is no research value in classifying them in these terms.

Results

Presented in the next pages are selected graphs which show the relevant data to the research questions. We focus here on three main factors and the correlation between them: **Time** for adaptation, **Levels** for recognition and **Age.**

Statistical analysis reveals the predictability of the hypothesis and the relevance of the results. Although professional statistical analysis was introduced only late in the process, it still shows that the basic test planning, the test methodology and the results are relevant and do have a value for themselves at present and for future tests.

Points to mention:

- The K factor calculation is the cd/m^2 measured in the back chamber with the target and divided by 6000cd/m^2 or 8000cd/m^2 according to the light level in the front chamber. Example: 432cd/m^2 measured in the back chamber divided by 6000cd/m^2 equals 0,072. **Therefore *Level 1* and *level 2* are synonymous to *factor-1* and *factor-2* or *K1* and *K2.***

- Two other parameters: gender and optics, which were recorded and analyzed, were found to have no influence on the results; therefore they are of no value and will not be presented in this report.

- We have used the help of Dr. Elias Said from STH KTH in analyzing the data and understanding it statistically. Dr. Said processed our raw data using “MINITAB” software, to meet with our research questions and our hypothesis.

Graphs for Regression Analysis

In graphs 1 and 2 we display the data in the form of regression analysis. The advantage of this statistical tool of regression analysis is that it can show if there is a relation between variables. This is also called correlation, and in this example we deal with three dependent variables: Time (visual adaptation) and Levels of recognition (K1/2 factor) versus one independent variable which is Age. These graphs show how strong is the correlation between these variables and this information is displayed by showing the Confidence Interval (CI) and the Prediction Interval (PI).

Regression Analysis: TIME_6 versus AGE_6

```
The regression equation is
TIME_6 = 0,4911 + 0,08782 AGE_6


S = 1,78449   R-Sq = 27,3%   R-Sq(adj) = 26,3%


Analysis of Variance

Source      DF       SS       MS      F      P
Regression   1   87,306  87,3063  27,42  0,000
Error       73  232,460   3,1844
Total       74  319,767
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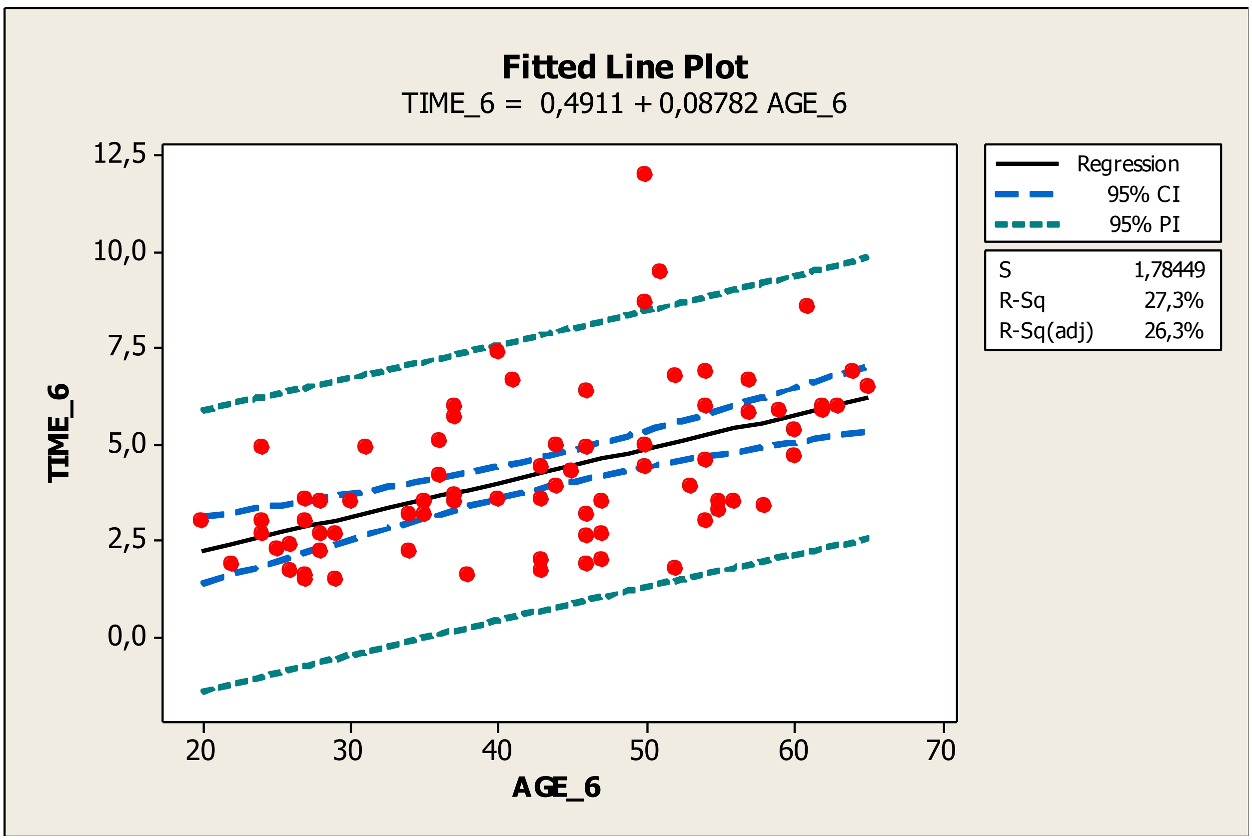

*Graph.1.*showing how time (adaptation) can be predicted within 95% when age is the independent value at 6000cd/m^2.

Regression Analysis: TIME_8 versus AGE_8

```
The regression equation is
TIME_8 = 0,0986 + 0,1081 AGE_8


S = 1,63252   R-Sq = 47,6%   R-Sq(adj) = 46,5%


Analysis of Variance

Source      DF       SS       MS      F      P
Regression   1  123,330  123,330  46,28  0,000
Error       51  135,921    2,665
Total       52  259,251
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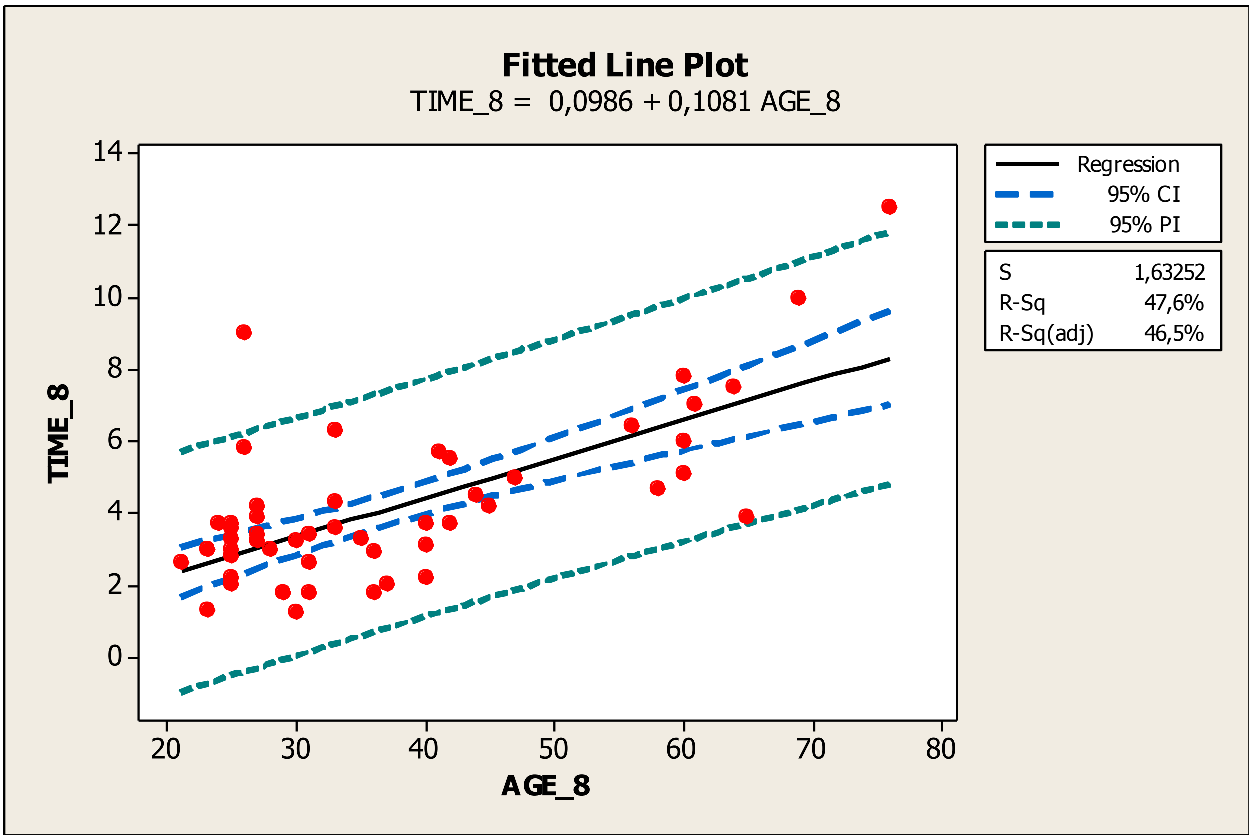
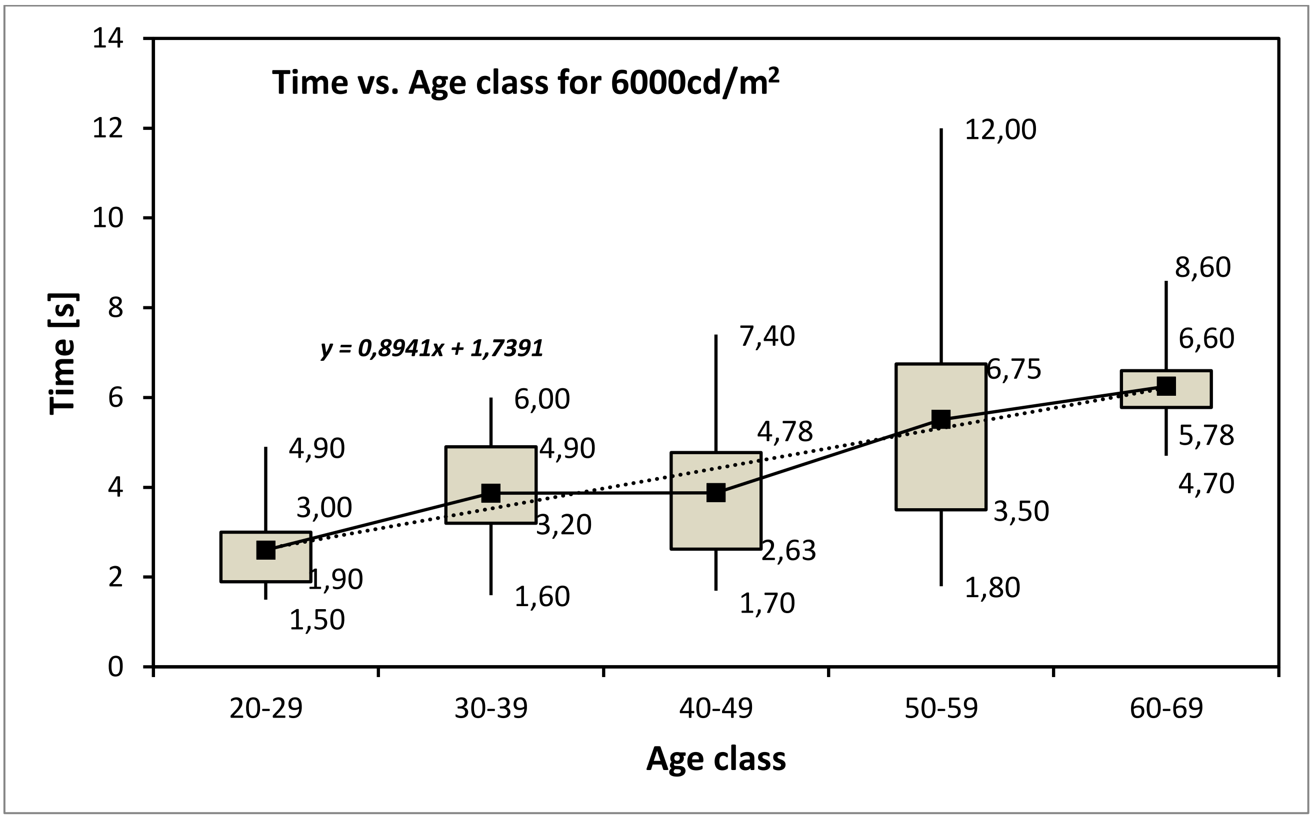


Graph.2. showing how time (adaptation) can be predicted within 95% when age is the independent value at 8000cd/m^2.

Box-Plot graphs

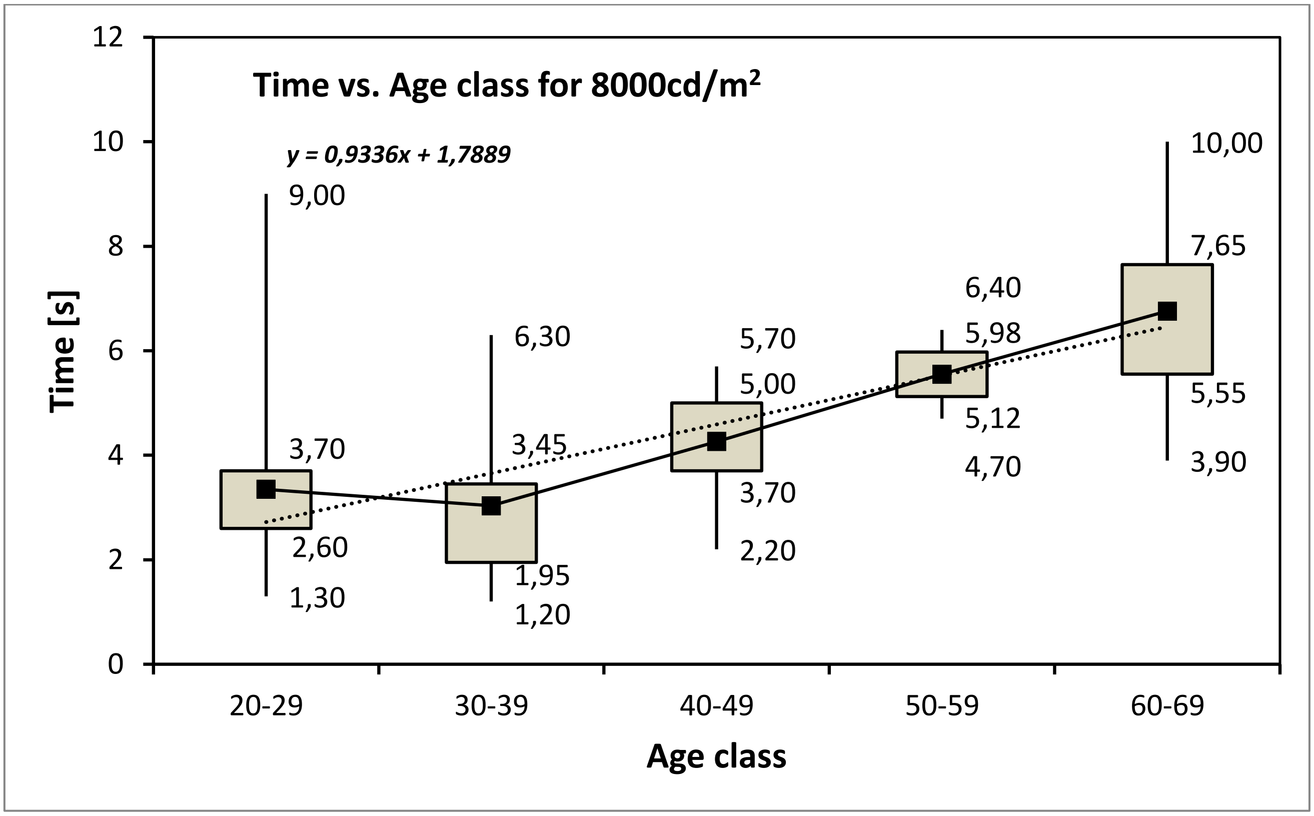
Graphs 3 and 4 show an analysis of the results for each initial light level with time versus age groups. They are displayed as *box–plot* graphs since this way represents “all in one”: max’ and min’ levels, medians and averages. The line connecting the dots represents the time average for the age classes. These *box-plot* graphs are showing the start quartile (25%), the end quartile (75%) and the highest and lowest recognition times.

Added to these graphs (below) are charts. These charts show the change in percentage for each age group mean. These percentages follow the full black line and are marked by the points on the line.



Graph.3.

6000 time Age	Seconds	Percentage
20-29	2,6	0%
20-29 to 30-39	3,87	48,80%
30-39 to 40-49	3,88	0,22%
40-49 to 50-59	5,51	42,10%
50-59 to 60-69	6,25	13,40%



Graph.4.

8000 time Age	Seconds	Percentage
20-29	3,35	0%
20-29 to 30-39	3,03	-9,55%
30-39 to 40-49	4,26	40,59%
40-49 to 50-59	5,55	30,28%
50-59 to 60-69	6,67	20,18%

Conclusions

Our main aim of investigation was regarding the visual adaptation curve of a driver entering a tunnel. The focus was on two main questions:

- **What level of luminance is needed inside a tunnel for the approaching driver at the exterior to recognize an obstacle within the tunnel?**

- **How long does it take for a driver to adapt from a high exterior level of luminance to a low interior level of luminance, given the condition that an obstacle is seen in the tunnel throughout the process?**

Our hypothesis:

Adaptation time, for a driver transiting from high light levels at exterior of tunnel and into low light levels into the interior of a tunnel, is in fact shorter than suggested in the current technical specifications. We attempt to conduct practical tests in order for us to validate or disproof this hypothesis.

Answers:

- **To what statistical probability is the hypothesis true?** 95%.
- **Is the data strong enough statistically for showing results?** The data is statistically **strong enough** to show results regarding adaptation time both when testing at 6000cd/m^2 and at 8000cd/m^2. This data shows clearly that adaptation time has a potential to be reduced substantially and that age has an immediate effect on it.
- The data is statistically **not strong enough** to show results regarding the *k-factor* at 8000cd/m^2, mainly due to lack of data. Whereas it shows a probability lower than 95% for a correlation between the age and the *k-factors* at 6000cd/m^2. It can also be said, perhaps in a more optimistic way, that age seems to have little influence on the *k-factor/*recognition levels according to our experiments at 6000cd/m^2 (graphs 5,11).
- A recommended new or different level of luminance inside the tunnel entrance cannot be suggested from the data we have. What can be said, is that according to the values collected for the *k-factors*, a level higher than 0,07 (which is the current technical recommendation for 155km/h) is not needed since all our experiment values are lower in means and only reach this level in max' values.
- A recommendation for 10 seconds adaptation time, for a driver transiting from high light levels at exterior of tunnel and into low light levels into the interior of a tunnel, seems to be a reasonable estimate according to our findings at this point.

Discussion

Going into answering our initial questions and validating our hypothesis is the first step. But as the nature of research is to answer questions, it should naturally provoke new questions. That is to be regarding the numerical data, the process of gathering it, the process of analyzing it and it should hopefully promote new fields of curiosity that might answer better - new and old questions.

The main matter to discuss, arising from the process up until now and seen from a point of view possible to acquire only at this stage, is regarding the actual value of the adaptation time as a parameter in itself and as a value put aside to the *k-factor*. We see that adaptation time can be reduced and we see that age is a factor directly correlated with adaptation time. The first point was an answer to the main question in this research. The second point probably isn't such a big surprise; we know as a fact that our visual system deteriorates with age and so we can assume logically that adaptation will take longer, amongst other effects to that. Having answered the question regarding adaptation time relatively easily, while at the same time getting inconclusive data regarding the *k-factor*, we must ask some questions:

1. Was the process correct?
2. Can adaptation time be "demoted" and is the *k-factor* to be used as the main parameter on which we should base a future research?
3. In what ways did this research promote us and in what ways can we plan better future phases for this research.

The process. As a whole yes, the process was correct considering the approach at the time of conceiving the methodology and the hypothesis. We had questions to answer, we had a certain level of knowledge and we planned accordingly and even with a certain level of sophistication and invention.

Technically, the physical 1:100 scale model worked very well. On the other hand, we lacked precision in conducting tests, e.g. Adaptation time in stage A not always measured for 2 precisely minutes, and considered as a critical error: not monitoring the tests done in quantity per type. That resulted in missing data to the *k-factor* analysis, especially at 8000cd/m^2.

K-factor. p.6, third paragraph in this report: *"Therefore, the curves shown in figures 1 and 2 are actually the graphical demonstration of the K-factor parameter in motion; they are showing the condition of recognizing an obstacle while adapting to low light levels in a tunnel. Adaptation is dependent on recognition and these are the two core topics of this research."* This quote comes to show that the answer to the second question was probably already in the introduction of this paper. The k-factor is probably the key factor to concentrate on since it is the element that must be visually recognized at all times and from this element other factors will be derived. For that reason it can be said that the initial focus on adaptation rather than on recognition was wrong strategically. Yet we might have not got this understanding if we wouldn't have chosen the path we have.

What can we learn about the K-factor from the data we do have? Looking at graphs 8 and 9 (appendix 1, p. 24), where age as the independent factor is replaced by frequency, we can see (only for 6000cd/m^2!) that the margin between means of levels (1 and 2) is 0,058 at level1 and 0,019 at level2. From that we can conclude that the K-factor might be in fact pretty lower than the suggested 0,07 (*Krav för vägars och gators utformning,* p.6 in this report). Level2 was tested as a reference to Level1. The idea was that it should give us a perspective to the results we get on Level1, which is the significant data we are after. What it reveals to us is actually the bottom line of recognition, a line not to go under. That means that Level1 can be acceptable from 0,02 and not needed higher than 0,07.

Future. The first and main gain from this research is that it directly approves of our hypothesis regarding the adaptation time. That means that we can regard the adaptation factor as being predictable and focus from here on the *k-factor,* which seems to be the dominant factor and on any other factors relevant or related.

Further future suggestions

Ideas and understandings for research continuation. As mentioned, what is presented in this report is a chapter in the greater research plan. Conclusions, discussions and suggestions are the result of the combination of the process and the figures and it can claim for meaningful information when only all the complete process has a logical thread and structure. Furthermore, as statistics is very much the use of a scientific method to answer research questions, the results naturally lead to even more questions and from there possibly to more research. To promote the success of the complete research, a number of issues should be considered and improved:

- Data we have gained and processed shows clear tendencies and promotes our hypothesis. However, better planning of tests regarding the quantity per age and the light levels (when using the scale model), will ensure reliability and will produce more complete graphs. This is a confidence enhancer to all tests and especially before approaching full scale tests. Also, it is important measure and test according to pre-determined guides. Not following these guides result in data that is less reliable and less scientific e.g. 1-2 minutes for adaptation instead of one determined time.
- When planning a full scale test one should work in three stages: 1. converting the results from the scale tests to full scale. Meaning that what we had done in controlled and predicted environments is probably only partly true to a real environment where multiple changing parameters are involved such as human behavior, fatigue, lighting conditions, weather, and other unpredictable parameters. 2. If needed, another session period of testing in scale with the model should be considered where specific, more focused tests are conducted. For example testing a certain age group at a certain light level. 3. Testing in full scale first on a small group of 2-4 persons who are taking part of the research is recommended. That will reveal, as much as possible, if the suggested plan for a full scale test is potentially good or bad. After that of course a full scale test should be executed and compared to the scale tests done with the model.

- Involving necessary external professionals in the process should be done not after starting the actual tests, but before. A stable process for conducting research is to plan as much as possible ahead and that must be considering the expertise and input of external professionals, especially regarding statistics which for many is not an expertise.

- **Testing the influence of tunnel approach on the adaptation curve.** We have started investigating this subject at the beginning July 2013. Lseq, which is the luminance veil of the access zone, changes the closer or further we are from the tunnel entrance. The whole image in front of a driver changes as he/she proceeds towards the tunnel and thus the luminance levels change and basically reduce gradually when we move towards the tunnel entrance. This reduction of luminance occurs since vegetation, buildings, rocks and any other physical object around the tunnel entrance portal gradually take the space of our visual view on the expense of the skylight, to eventually disappear completely once we enter the threshold zone. What we were starting to investigate, or reflect on, is what is the actual reduction of light and to what extent it influences, prematurely, our adaptation towards the tunnel entrance. That is another tool to improve tunnel entrance lighting by analyzing, using the L20 method for example (but not necessarily the only method), the reduction of light on the approach and how that can influence the lighting configuration of the entrance portal.

Fig.7: Photos taken on 2013/07/02 at the northern entrance of Häggvik tunnel. On the bottom row, showing photos taken using an LMK luminance camera, the L20 circle of $2X10^0$ is positioned in an attempt to gather data about the influence of the light levels changing towards the tunnel entrance.

Summary

This paper aims at representing a process which is devoted for the improvement of tunnel lighting. We tried to show the motivations, the methodology and the results as a logical development of ideas through practical experiments. Answering our initial research questions produced new questions, and that is a sign of a creative and open process. The knowledge gained here comes not only from the conclusions we reached, but just as well from the process itself.

My personal opinion is that the real engine for this research, beyond the practical motivation for better tunnel lighting, is the attitude promoted by the initiators from Trafikverket and shared by the Lighting Laboratory at KTH. Hopefully, we were able to broaden our knowledge and lay down a better basis for continuation.

Special thanks to Henrik, Petter, Elias, Thomas and Jan.

Appendix 1. Additional graphs

Regression Analysis: FACTOR1_6 versus AGE_6

```
The regression equation is
FACTOR1_6 = 0,04137 + 0,000358 AGE_6


S = 0,0169339   R-Sq = 4,9%   R-Sq(adj) = 2,8%


Analysis of Variance

Source      DF         SS         MS     F      P
Regression   1  0,0006540  0,0006540  2,28  0,138
Error       44  0,0126173  0,0002868
Total       45  0,0132713
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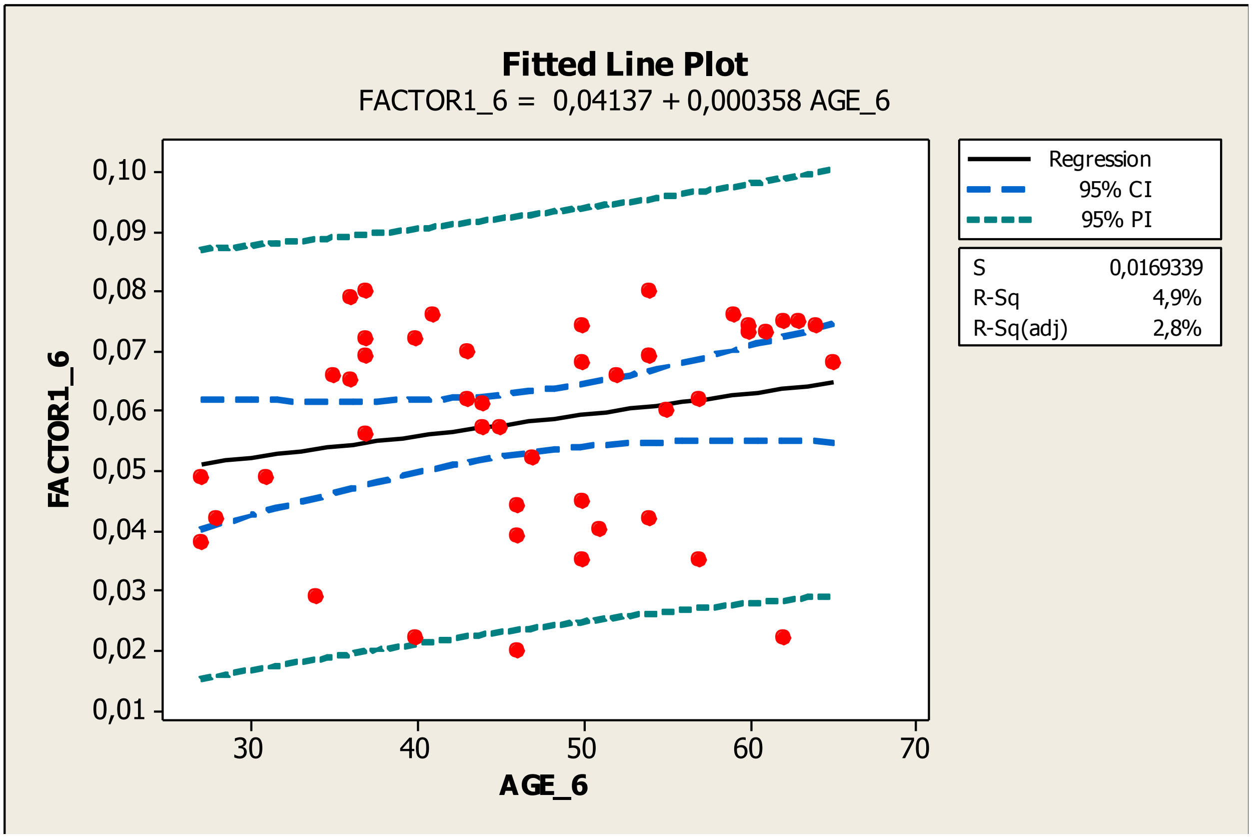


Graph.5 showing how K factor1 could not be predicted to follow the age value.

Although graphs 5 and 6 shows us we cannot reject the *null hypothesis* for K1 versus age at 6000cd/m^2, it does show we can still have a prediction less than 95% accurate. In this case, where age appears not to be a significant factor, we should look at graphs 8 (p.24), 11 (p.26) and 19 (p.33). There we can recognize better the margin where these results do give us useful information. We see there that 0,08 is the highest k-factor value, we see that 0,02 is the lowest k-factor and we see that most measurements are between 0,05 and 0,07 with a mean of 0,058.

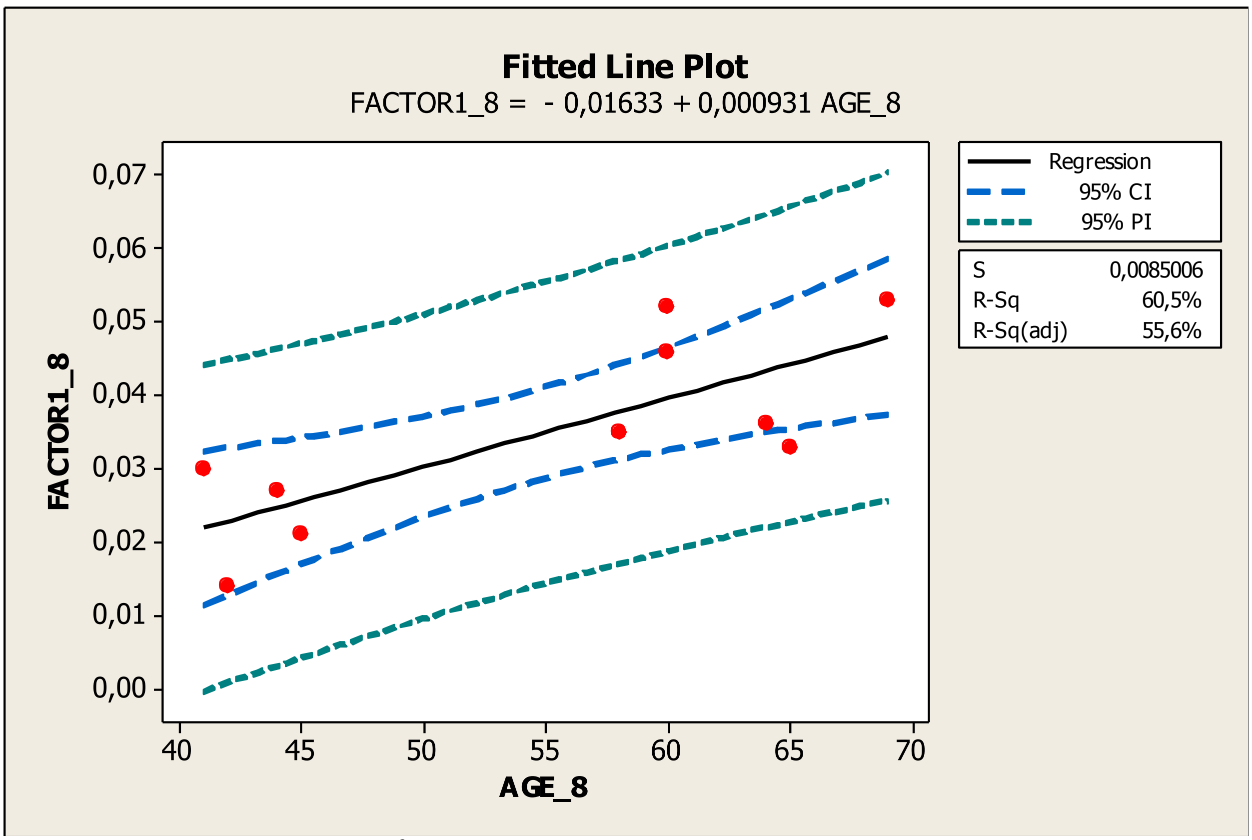
Regression Analysis: FACTOR1_8 versus AGE_8

```
The regression equation is
FACTOR1_8 = - 0,01633 + 0,000931 AGE_8


S = 0,00850056   R-Sq = 60,5%   R-Sq(adj) = 55,6%


Analysis of Variance

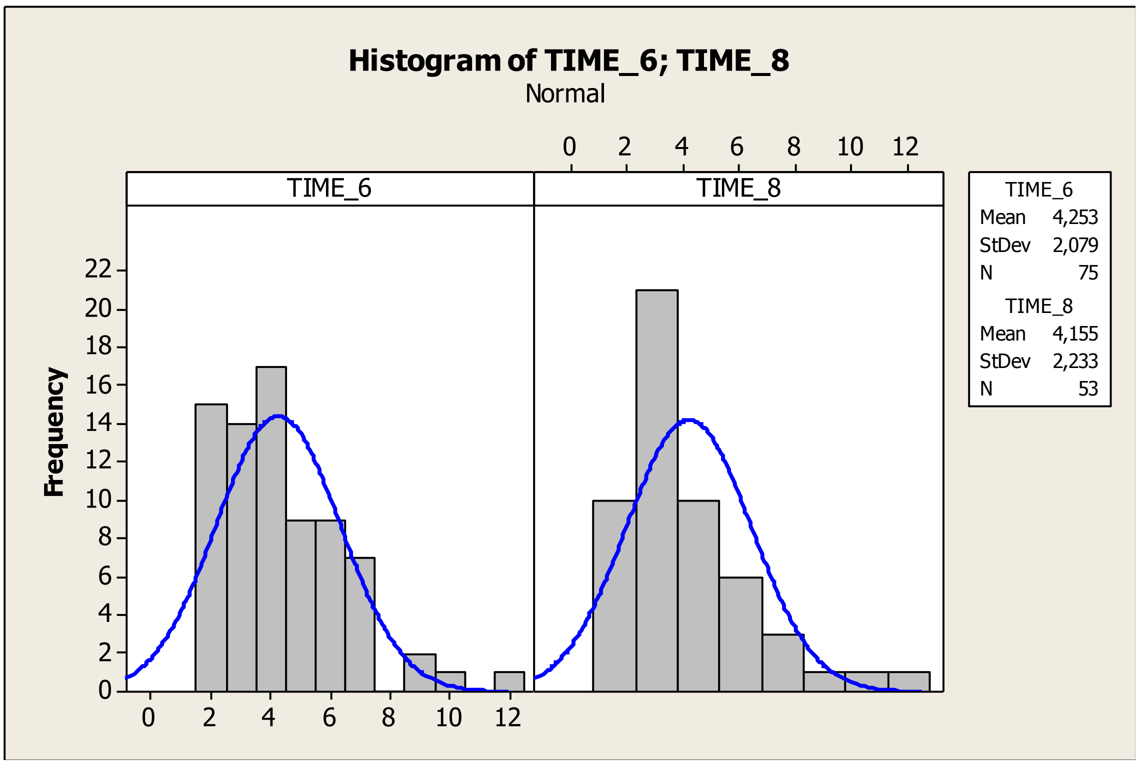
Source      DF         SS         MS      F      P
Regression   1  0,0008860  0,0008860  12,26  0,008
Error        8  0,0005781  0,0000723
Total        9  0,0014641
```



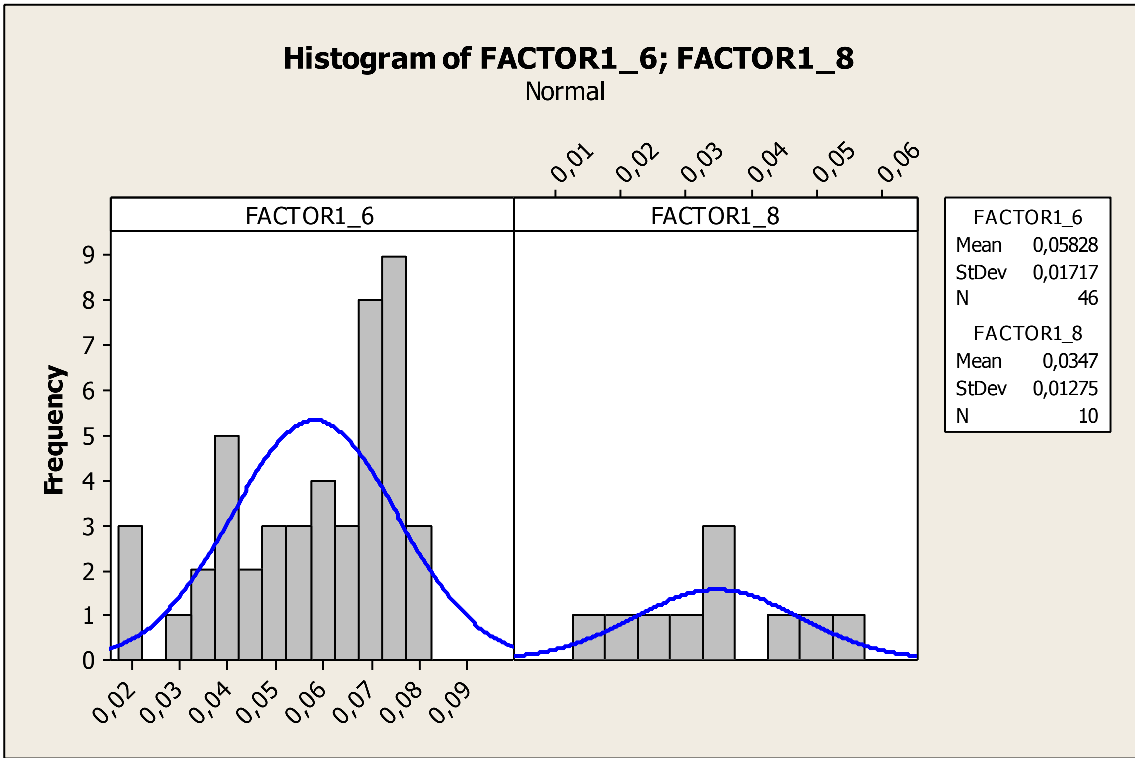
Graph.6. showing how for 8000cd/m^2 data is simply not sufficient.

In graphs 7-9 we present the data as a graphical introduction and as a comparison between 6000cd/m^2 and 8000cd/m^2 in general, when Frequency is our independent variable and time and levels are the dependent variables. Age is not represented in these graphs and that makes them valuable as an overview where we can look at the mean values for the complete test group.

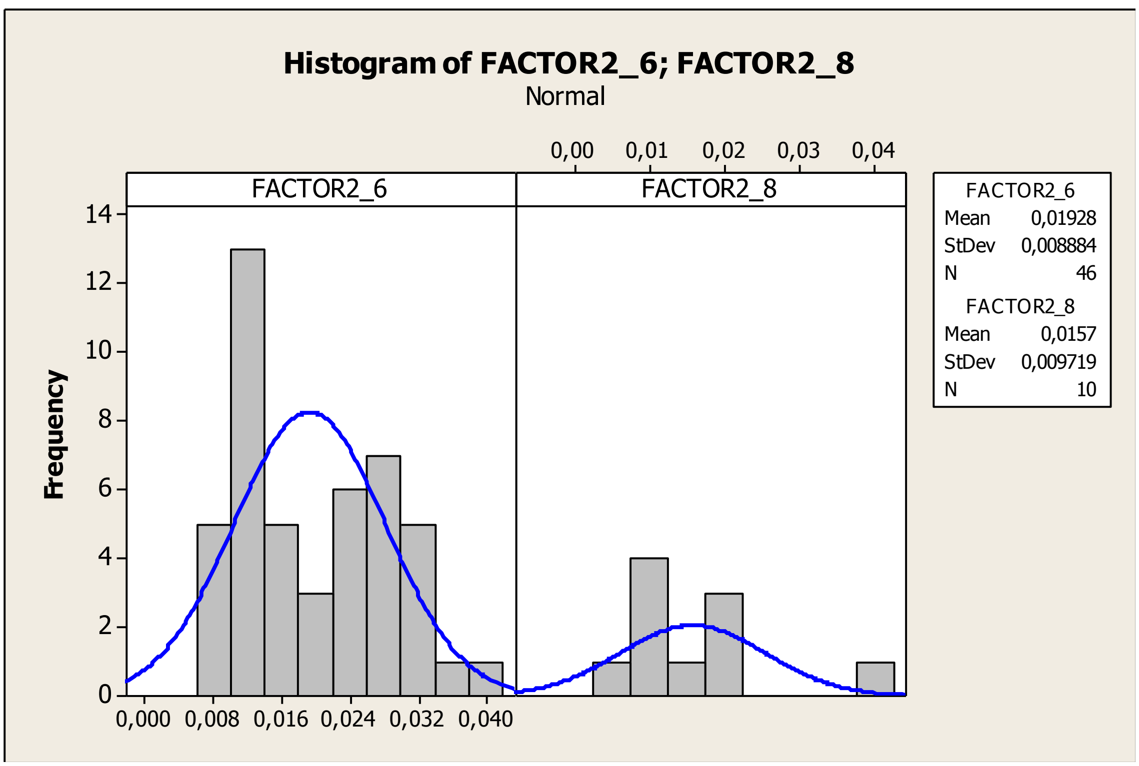
A better comparison between 6000cd/m^2 and 8000cd/m^2 is made when Time is a variable (graph 7), since we have sufficient data. When comparing the *K-factors* we lack enough data at 8000cd/m^2.



Graph.7. Histogram showing Time versus Frequency for 6000cd/m^2 and 8000cd/m^2, without age class.



Graph.8. Histogram showing K1 versus Frequency for 6000cd/m^2 and 8000cd/m^2, without age class.



Graph.9. Histogram showing K2 versus Frequency for 6000cd/m^2 and 8000cd/m^2, without age class.

By Dr. Elias Said,

ANOVA: the analysis of variance.

The statistical model used in this study is based on testing the equality of several means (averages) of the recorded data. This statistical model is used to analyze the difference between group means and their associated procedures, such as variation among and between groups as age groups. ANOVA is useful in comparing three or more means for statistical significance. The model is basically meant to test if the null hypothesis is valid within a confidence interval. The meaning of Null hypothesis is that there is no significant difference of means. The rejection of the null hypothesis is based on a level of significance called the P-value. The P-value is defined as the smallest level of significance that would lead to rejection of the null hypothesis. Usually a confidence interval at 95% is chosen, which means that if the calculated P-value is less than 0.05 the null hypothesis is rejected and it is concluded that there is a difference between the group means.

The ANOVA test below (graphs 4-9) shows that the mean values of time differ between the age groups (P-value < 0.05 for both data 6000cd/m^2 and 8000cd/m^2). In addition it is worth to mention that the use of this model is adequate when examining the residuals plots. The residual plot for this analysis shows that the mean of the error is approximately zero. The ANOVA test also shows that there is no significant difference of means between the age and the factors 1 and 2 (calculated P-value > 0.05).

P-values in graphs are marked in green where the Null hypothesis is rejected and in yellow when it is accepted - no significant difference of means. Or in other words: Age is seen as influencing time (adaptation) for a probability of at least 95%, whereas for the *k-factors* the effect is disputed since data is not sufficient to conclude the same when using ANOVA.

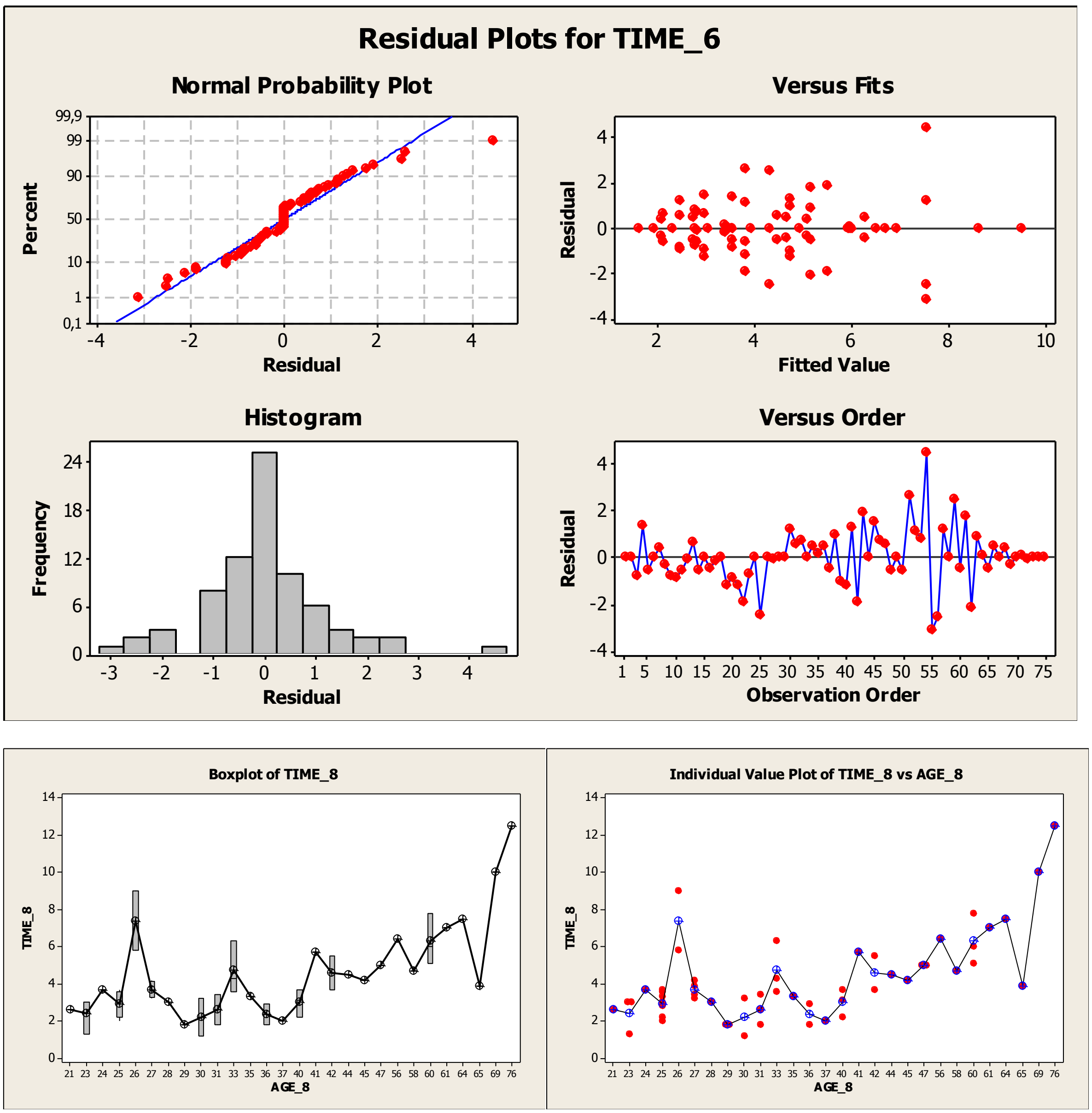
The analysis of variance, ANOVA: Confidence interval and regression analysis.

One-way ANOVA: TIME_6 versus AGE_6

```
Source  DF      SS     MS     F      P
AGE_6   37  219,02   5,92  2,17  0,010
Error   37  100,75   2,72
Total   74  319,77

S = 1,650   R-Sq = 68,49%   R-Sq(adj) = 36,99%

Pooled StDev = 1,650
```

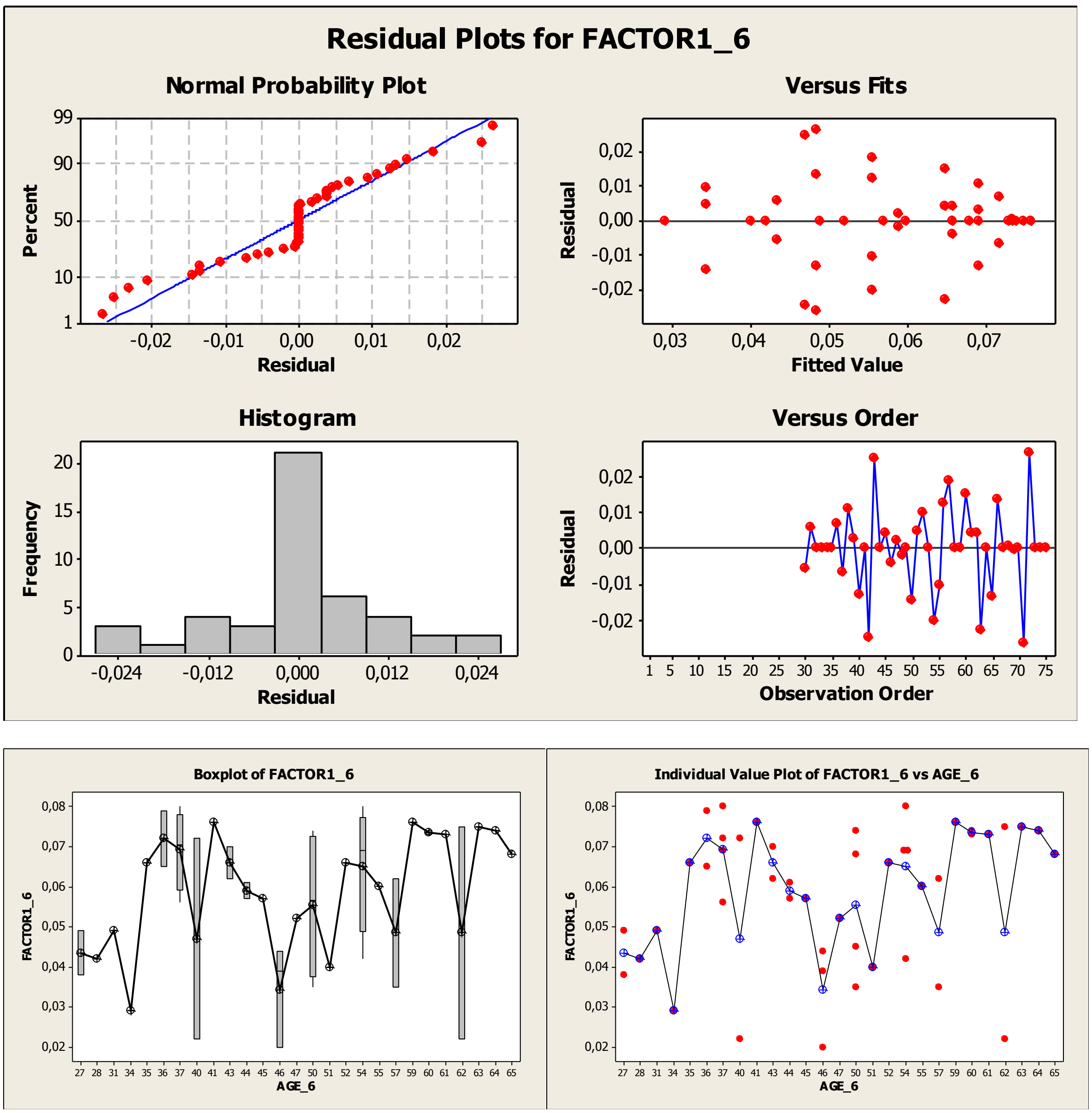


Graph.10.

One-way ANOVA: FACTOR1_6 versus AGE_6

```
Source   DF        SS        MS     F      P
AGE_6    26  0,007619  0,000293  0,99  0,523
Error    19  0,005652  0,000297
Total    45  0,013271

S = 0,01725   R-Sq = 57,41%   R-Sq(adj) = 0,00%
Pooled StDev = 0,01725
```



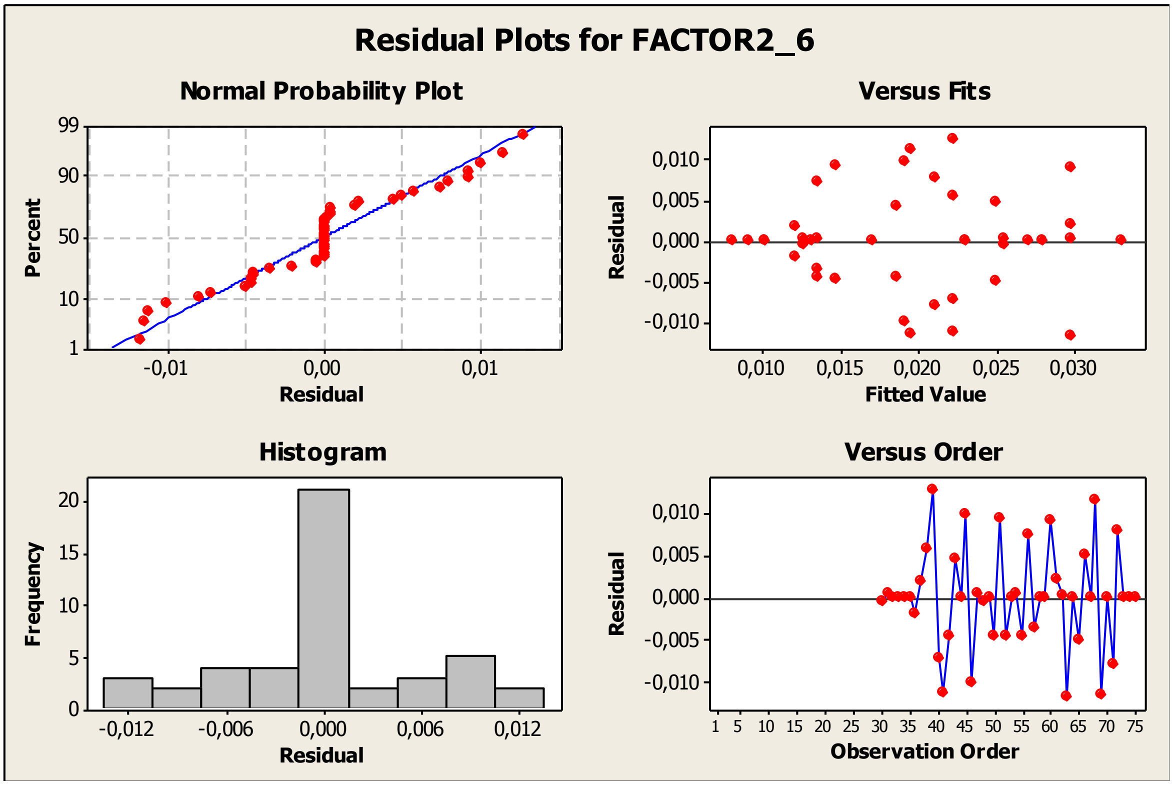
Graph.11.

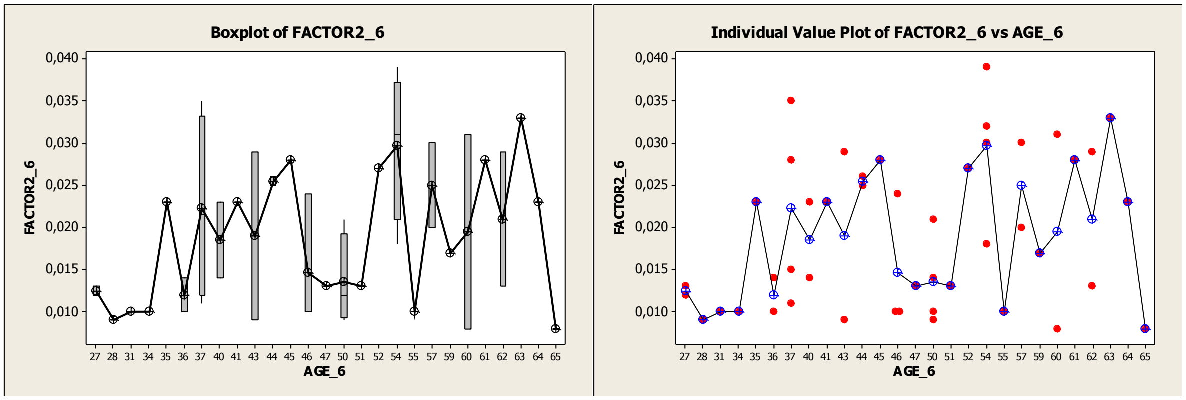
One-way ANOVA: FACTOR2_6 versus AGE_6

```
Source   DF         SS          MS     F      P
AGE_6    26  0,0020362  0,0000783  0,98  0,526
Error    19  0,0015152  0,0000797
Total    45  0,0035513

S = 0,008930   R-Sq = 57,34%   R-Sq(adj) = 0,00%

Pooled StDev = 0,008930
```





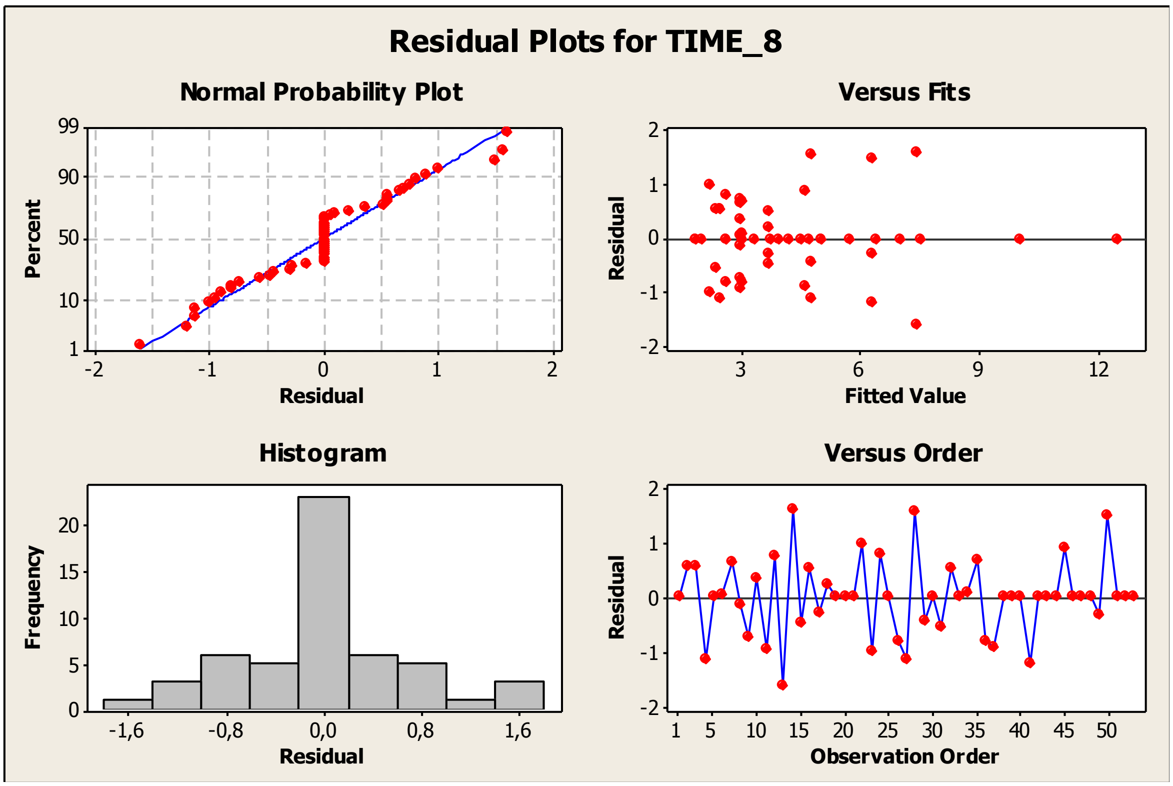
Graph.12.

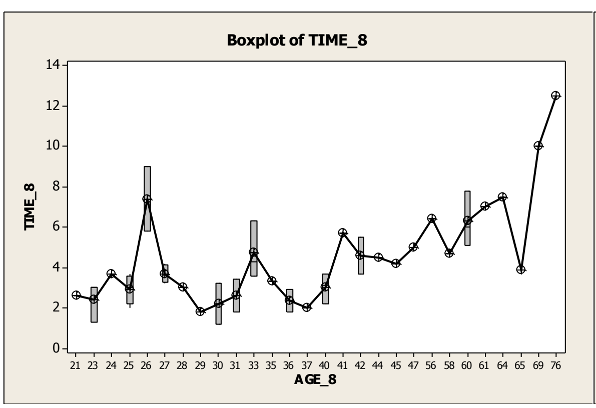
One-way ANOVA: TIME_8 versus AGE_8

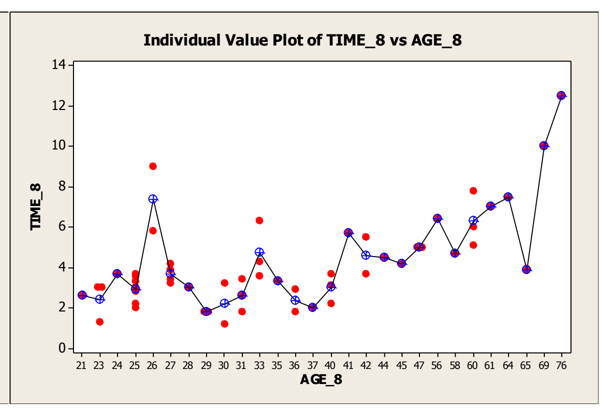
Source	DF	SS	MS	F	P
AGE_8	27	234,628	8,690	8,82	0,000
Error	25	24,623	0,985		
Total	52	259,251			

S = 0,9924   R-Sq = 90,50%   R-Sq(adj) = 80,24%

Pooled StDev = 0,992







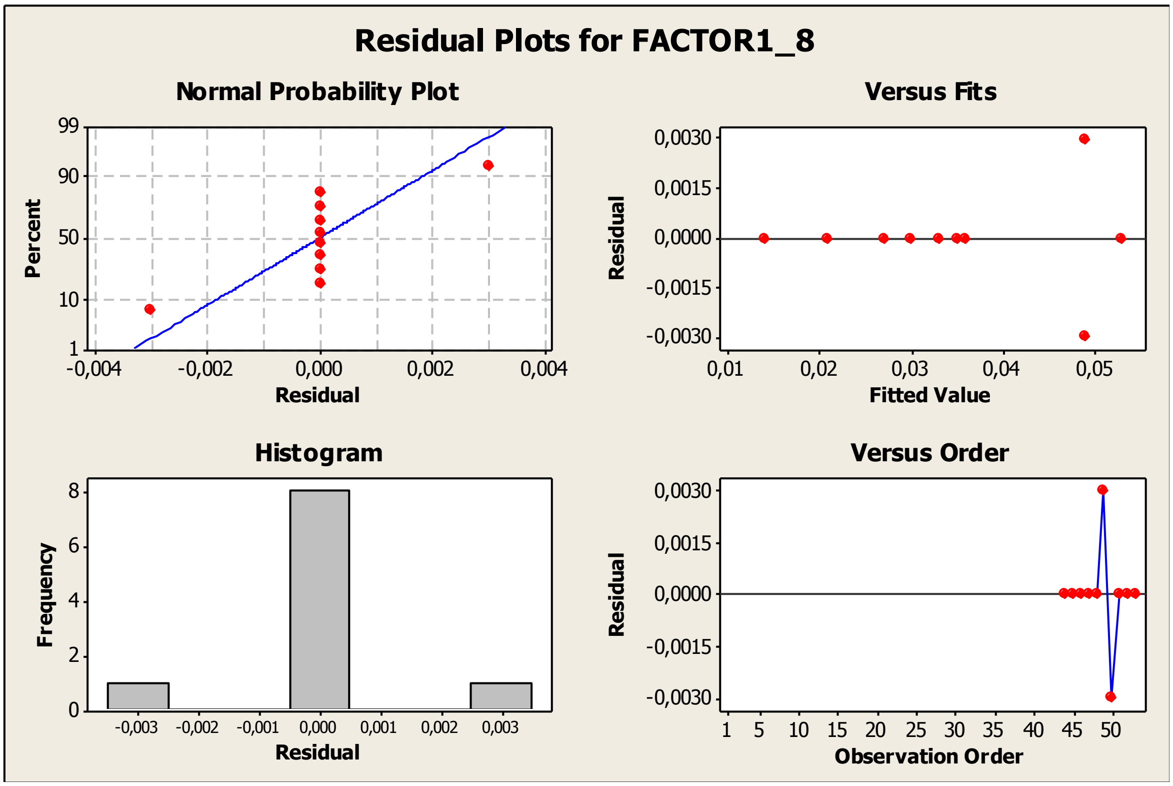
Graph.13.

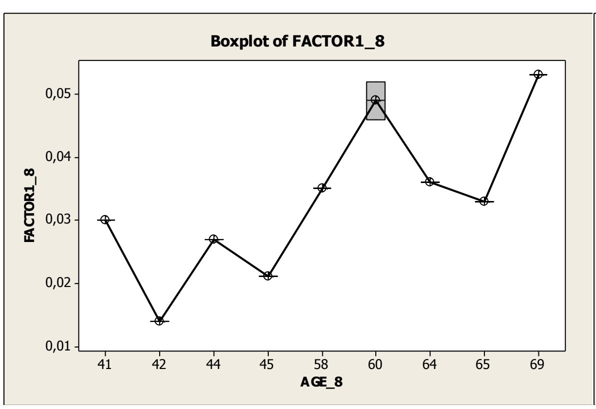
One-way ANOVA: FACTOR1_8 versus AGE_8

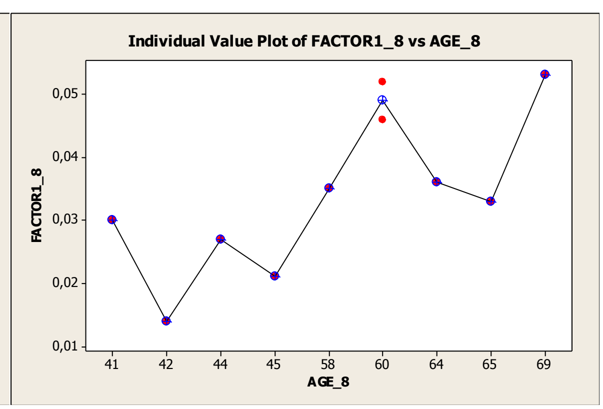
Source	DF	SS	MS	F	P
AGE_8	8	0,0014461	0,0001808	10,04	0,240
Error	1	0,0000180	0,0000180		
Total	9	0,0014641			

S = 0,004243   R-Sq = 98,77%   R-Sq(adj) = 88,94%

Pooled StDev = 0,00424







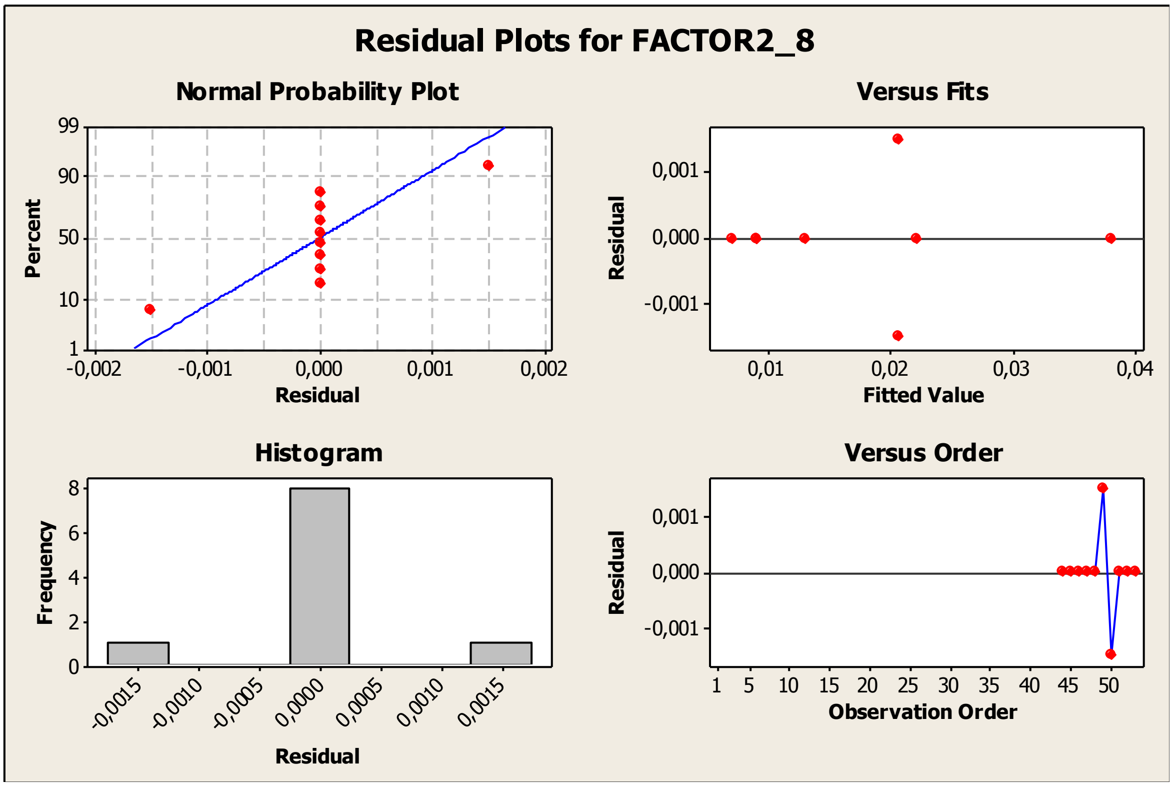
Graph.14.

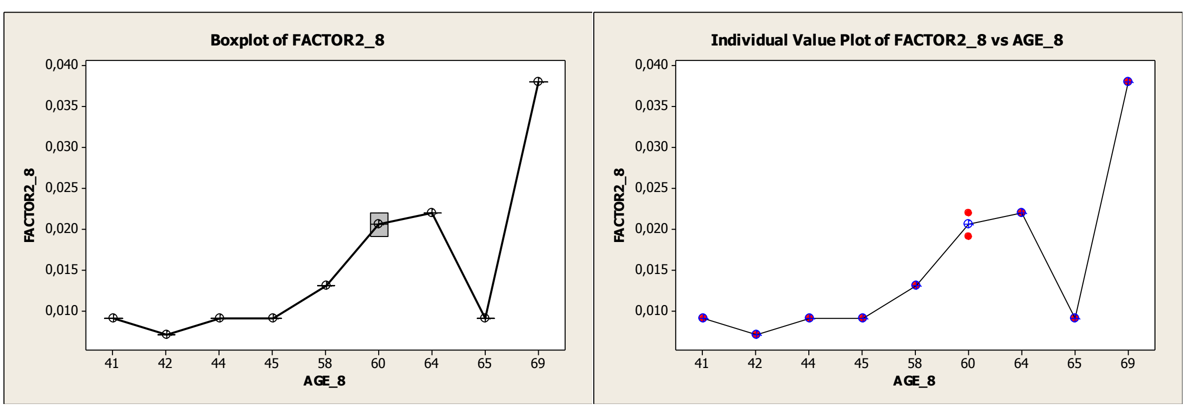
One-way ANOVA: FACTOR2_8 versus AGE_8

```
Source  DF         SS         MS      F      P
AGE_8    8  0,0008456  0,0001057  23,49  0,158
Error    1  0,0000045  0,0000045
Total    9  0,0008501

S = 0,002121   R-Sq = 99,47%   R-Sq(adj) = 95,24%

Pooled StDev = 0,002121
```





Graph.15.

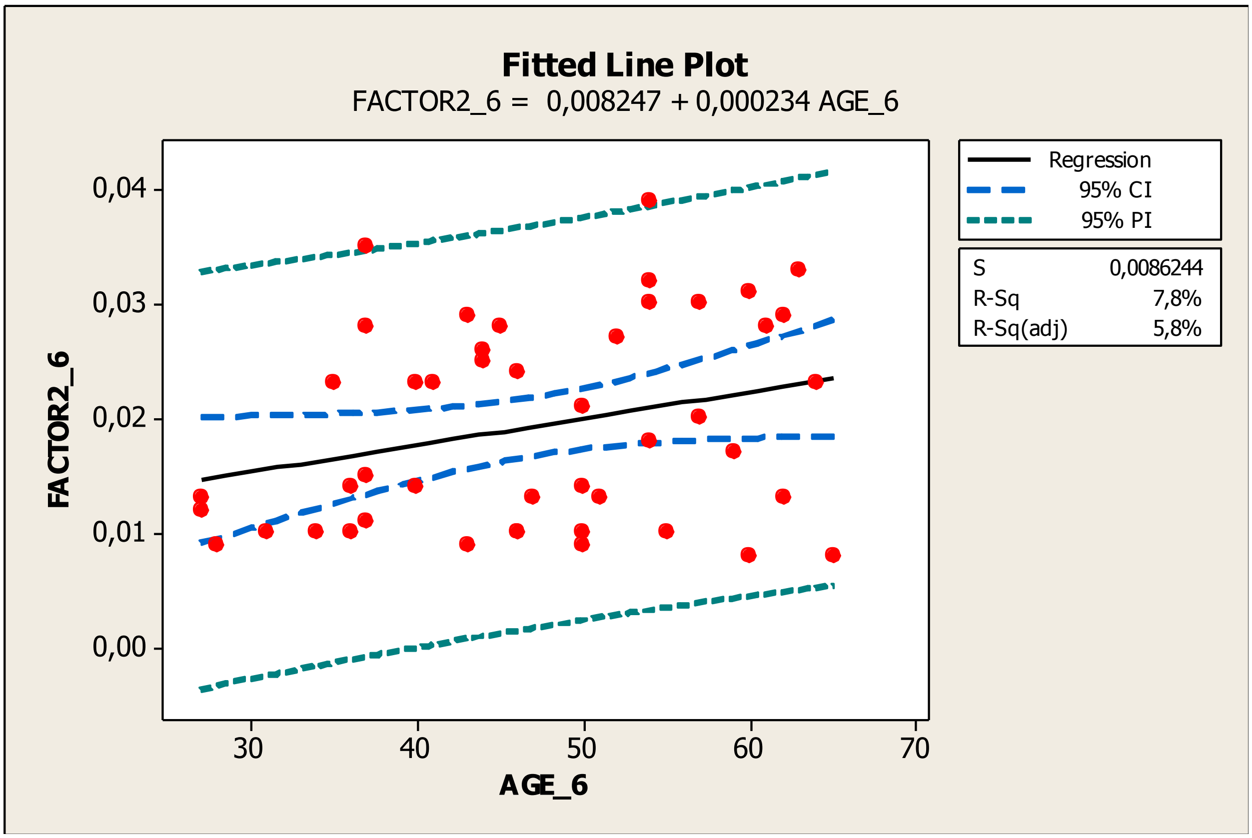
Regression Analysis: FACTOR2_6 versus AGE_6

```
The regression equation is
FACTOR2_6 = 0,008247 + 0,000234 AGE_6


S = 0,00862438   R-Sq = 7,8%   R-Sq(adj) = 5,8%


Analysis of Variance

Source      DF         SS         MS     F      P
Regression   1  0,0002786  0,0002786  3,75  0,059
Error       44  0,0032727  0,0000744
Total       45  0,0035513
```



Graph.16.

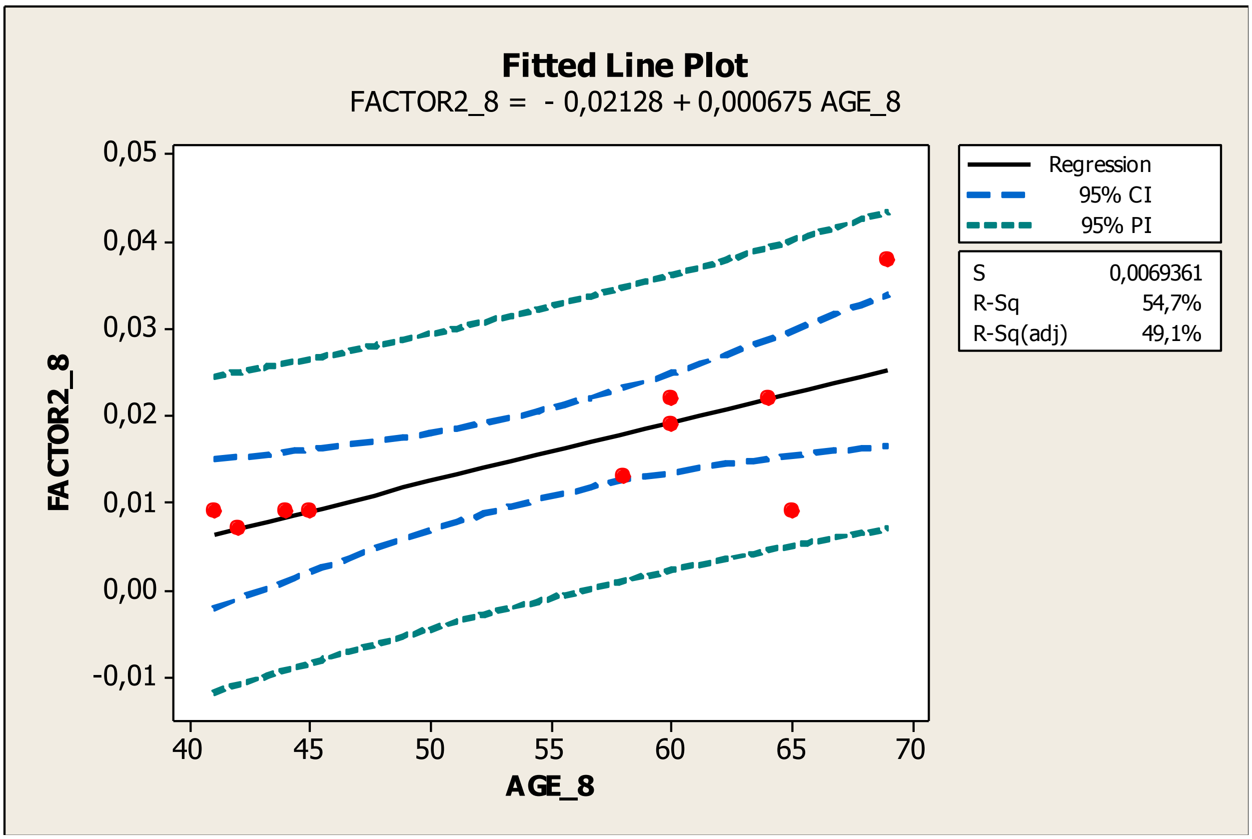
Regression Analysis: FACTOR2_8 versus AGE_8

```
The regression equation is
FACTOR2_8 = - 0,02128 + 0,000675 AGE_8

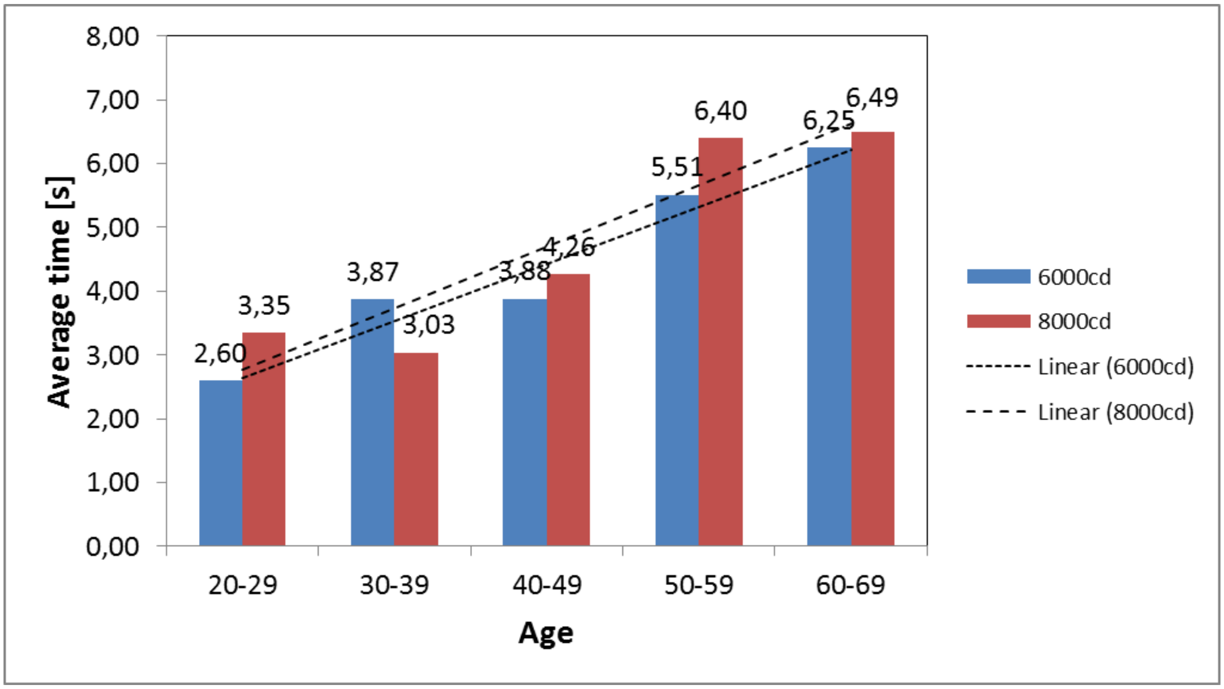

S = 0,00693611   R-Sq = 54,7%   R-Sq(adj) = 49,1%


Analysis of Variance

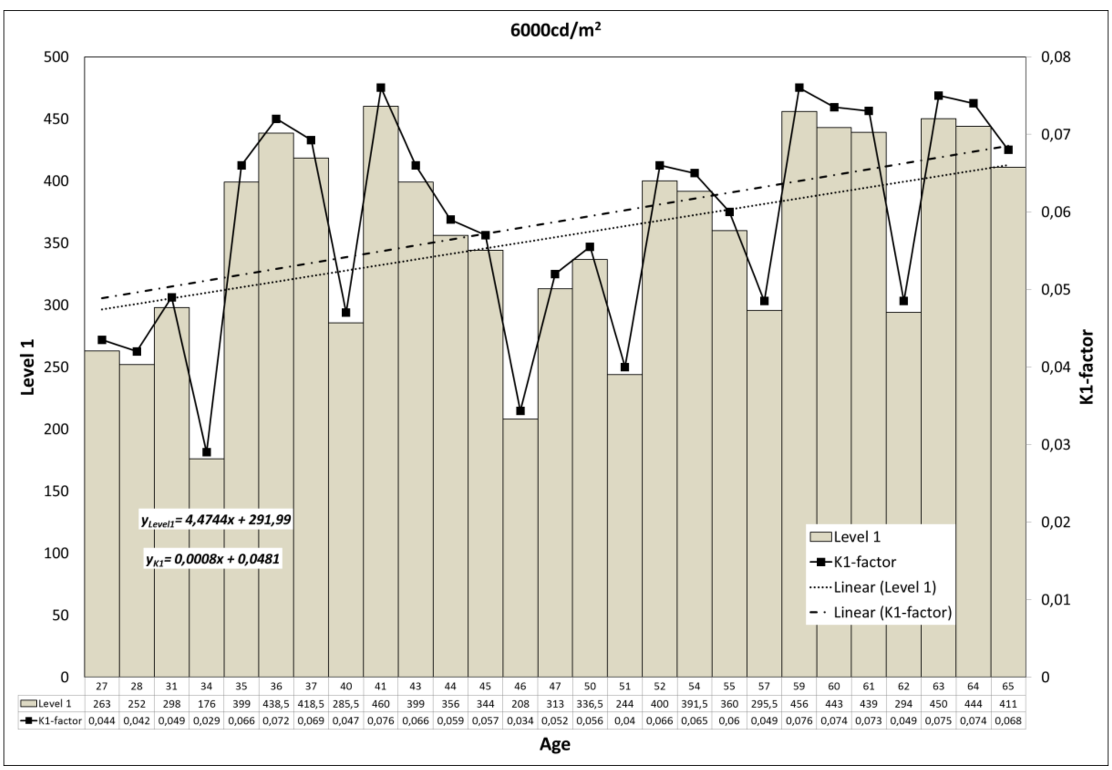
Source      DF         SS         MS     F      P
Regression   1  0,0004652  0,0004652  9,67  0,014
Error        8  0,0003849  0,0000481
Total        9  0,0008501
```



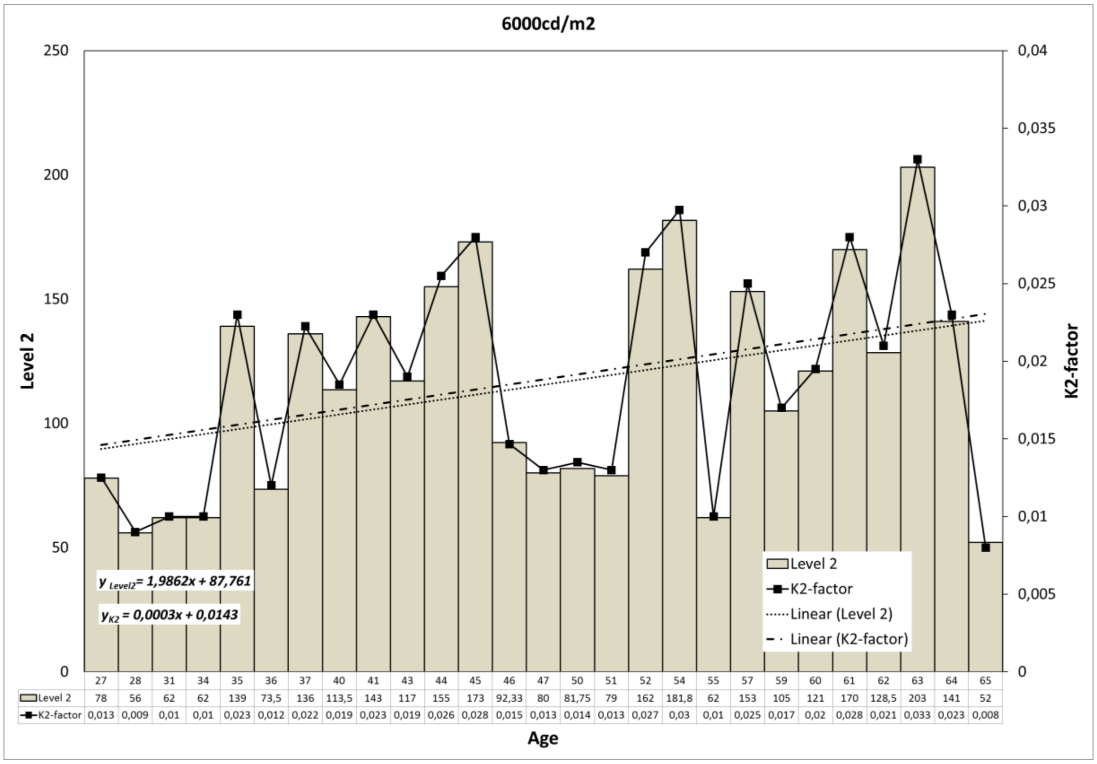
Graph.17.



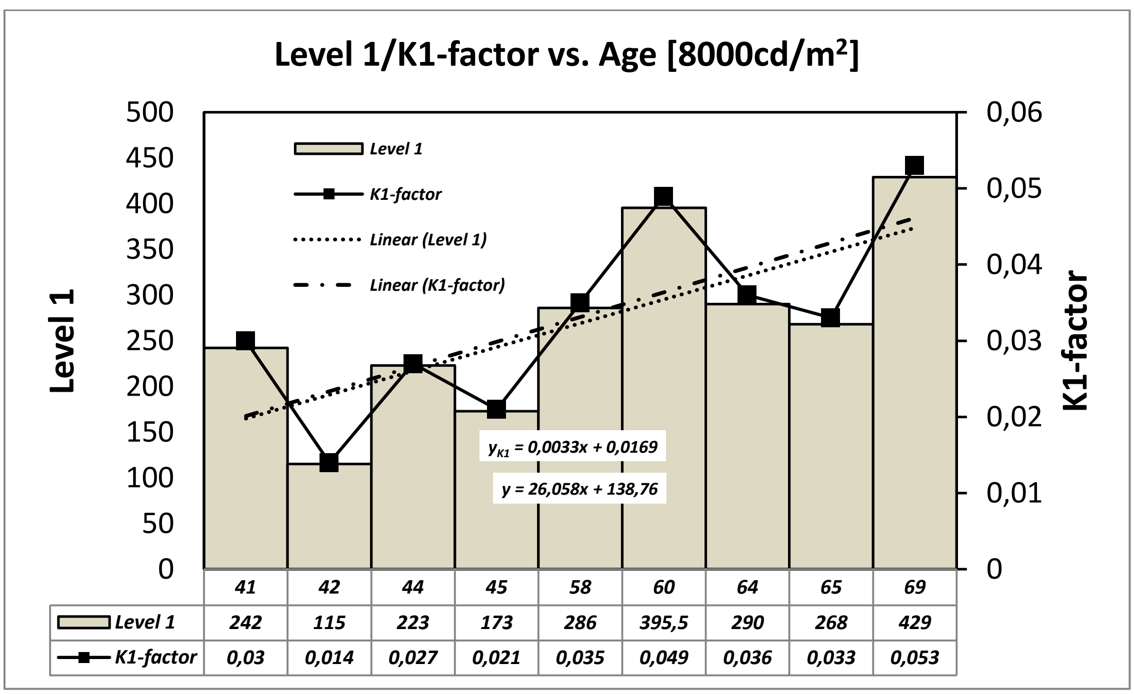
Graph.18. Time Vs. Age combined. This graph shows in bars the average adaptation time for every age group. Linear lines show the slope of change according to age class.



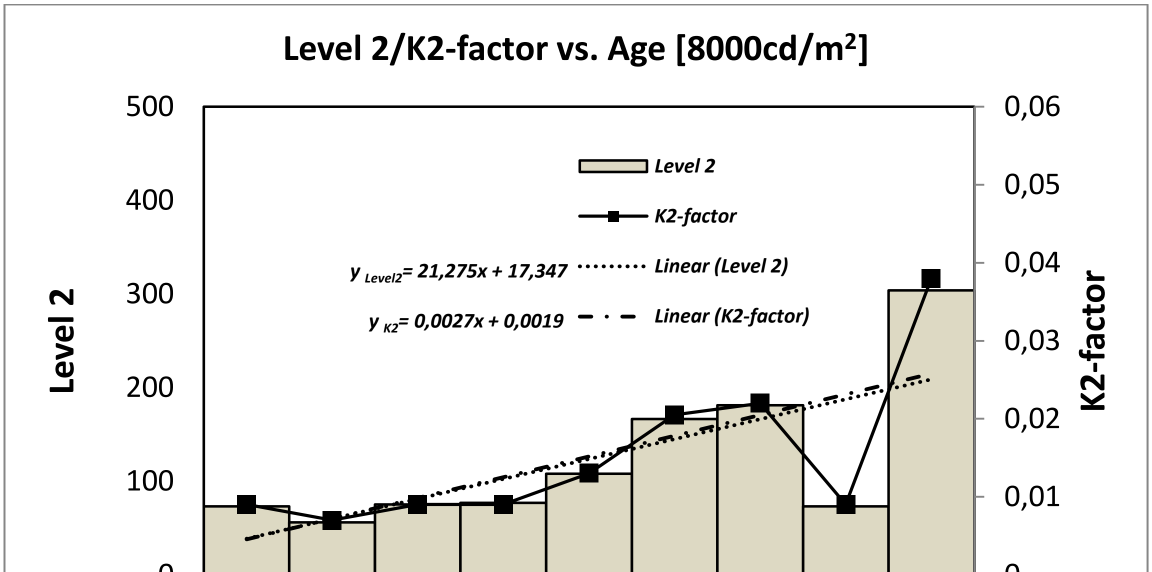
Graph.19. K1/Level1 Vs. Average of ages at 6000cd/m^2.



Graph.20. K2/Level 2 Vs. Average of ages at 6000cd/m^2



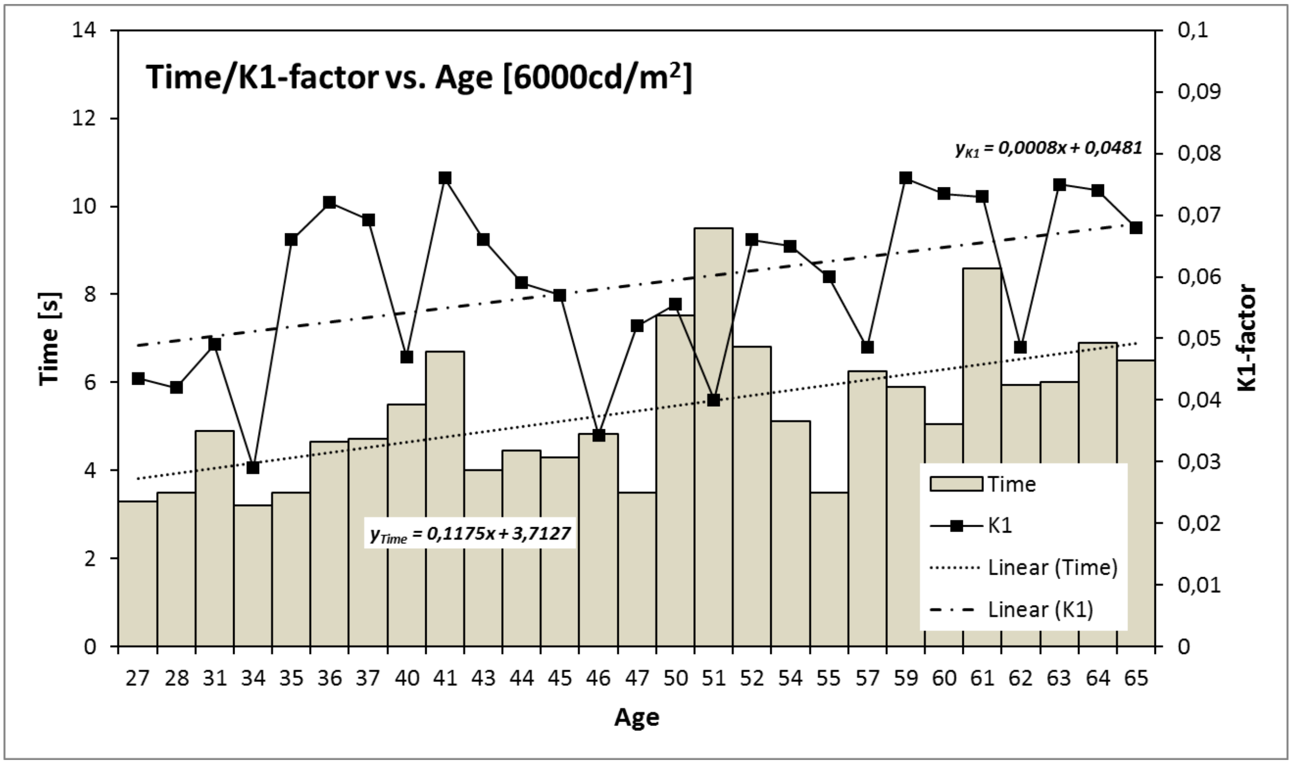
Graph.21. K1/Level1 Vs. Average of ages at 8000cd/m^2.



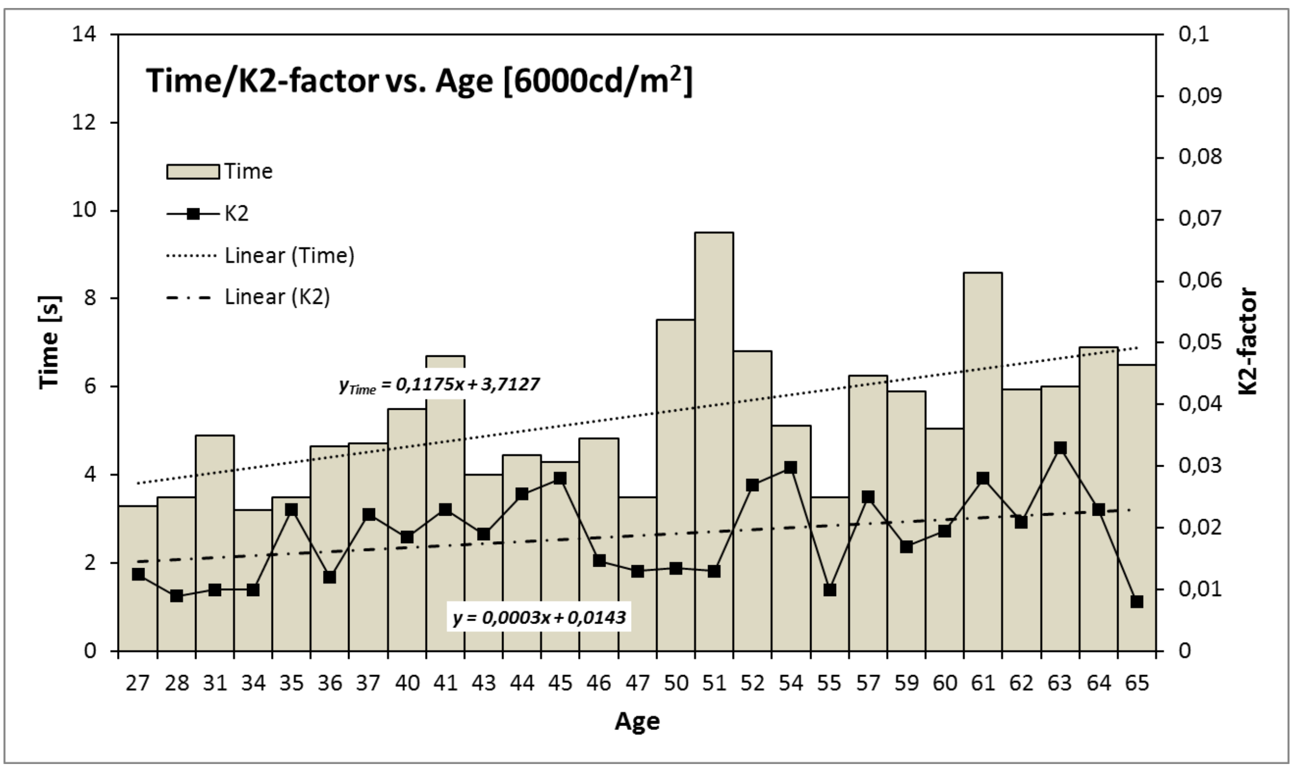
	41	42	44	45	58	60	64	65	69
Level 2	73	56	75	77	108	166,5	181	73	304
K2-factor	0,009	0,007	0,009	0,009	0,013	0,0205	0,022	0,009	0,038

Graph.22. K2/Level2 Vs. Average of ages at 6000cd/m^2.

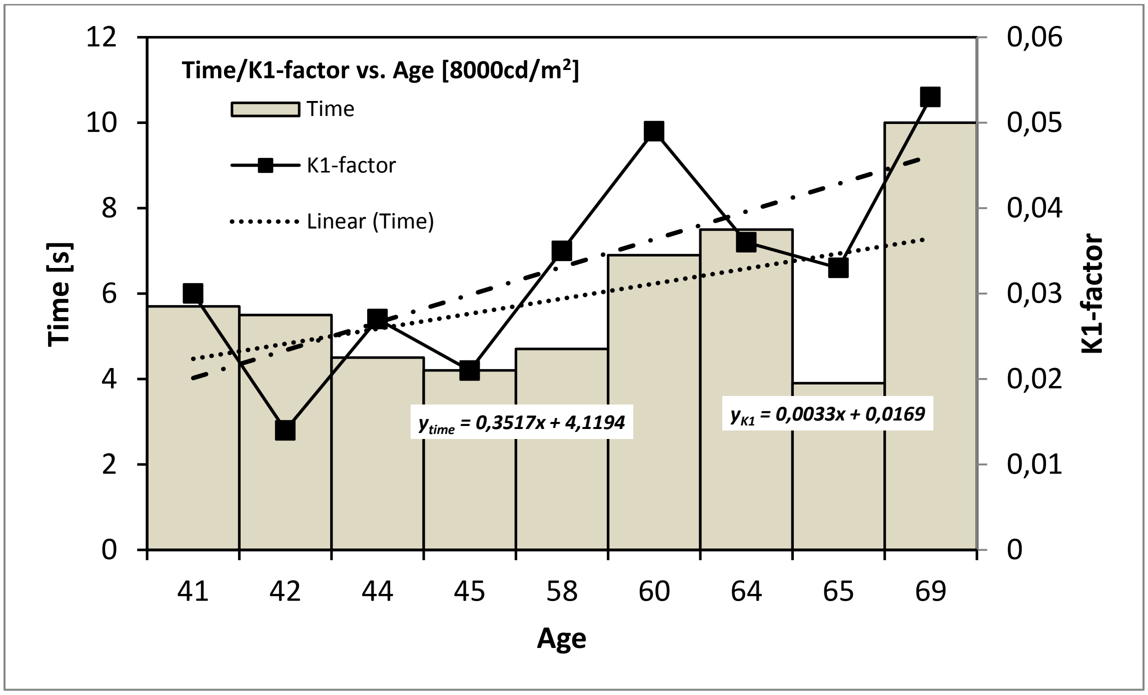
Graphs 19-22 showing K1 and K2 (as Levels 1&2) versus Age. Notice that this is all the data we have for Levels at 8000cd/m^2, while data for Levels at 6000cd/m^2 is more abundant. In fact every one of these graphs shows within 4 different ways to represent the K factor data and even if not as uniformed as *Time Vs. Age*, A tendency is seen with the linear data. However this data is not statistically valid and therefore not presented as fact or as having 95% probability.



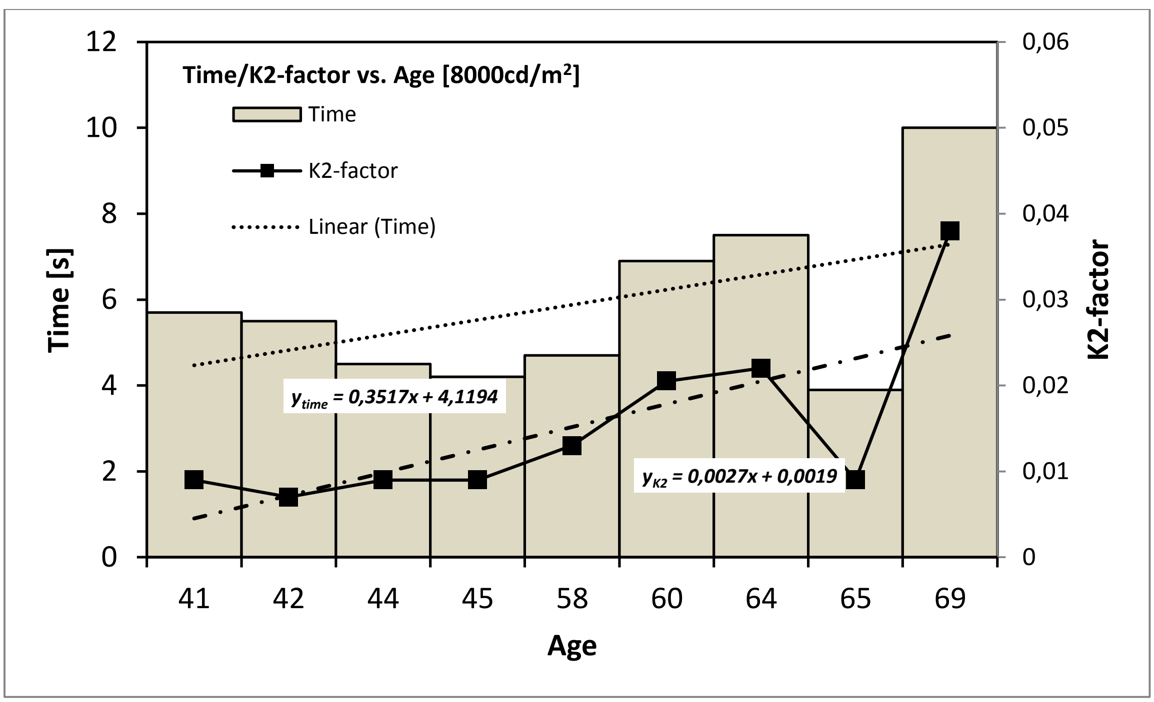
Graph.23. Time Vs. K1 Vs. age at 6000cd/m^2 at average of ages.



Graph.24. Time Vs. K2 Vs. age at 6000cd/m^2 at average of ages.



Graph.25. Time Vs. K1 Vs. age at 8000cd/m^2 at average of ages.



Graph.26. Time Vs. K2 Vs. age at 8000cd/m^2 at average of ages.

Raw data 8000cd/m^2

8000	AGE	TIME	LEVEL 1	FACTOR 1	LEVEL 2	FACTOR 2
	21	2,6				
	23	3				
	23	3				
	23	1,3				
	24	3,7				
	25	3				
	25	3,6				
	25	2,8				
	25	2,2				
	25	3,3				
	25	2				
	25	3,7				
	26	5,8				
	26	9				
	27	3,2				
	27	4,2				
	27	3,4				
	27	3,9				
	28	3				
	29	1,8				
	29	1,8				
	30	3,2				
	30	1,2				
	31	3,4				
	31	2,6				
	31	1,8				
	33	3,6				
	33	6,3				
	33	4,3				
	35	3,3				
	36	1,8				
	36	2,9				
	37	2				
	40	3,1				
	40	3,7				
	40	2,2				
	42	3,7				
	47	5				

	47	5				
	56	6,4				
	60	5,1				
	61	7				
	76	12,5				
	41	5,7	242	0,03	73	0,009
	42	5,5	115	0,014	56	0,007
	44	4,5	223	0,027	75	0,009
	45	4,2	173	0,021	77	0,009
	58	4,7	286	0,035	108	0,013
	60	6	416	0,052	176	0,022
	60	7,8	375	0,046	157	0,019
	64	7,5	290	0,036	181	0,022
	65	3,9	268	0,033	73	0,009
	69	10	429	0,053	304	0,038

Raw data 6000cd/m^2

6000	AGE	TIME	LEVEL 1	FACTOR 1	LEVEL 2	FACTOR 2
	20	3				
	22	1,9				
	24	2,7				
	24	4,9				
	24	3				
	25	2,3				
	26	2,4				
	26	1,7				
	27	1,6				
	27	1,5				
	28	2,2				
	28	2,7				
	29	2,7				
	29	1,5				
	30	3,5				
	34	2,2				
	35	3,2				

	38	1,6				
	43	1,7				
	43	2				
	46	2,6				
	46	1,9				
	47	2				
	47	2,7				
	52	1,8				
	53	3,9				
	55	3,3				
	56	3,5				
	58	3,4				
	27	3,6	229	0,038	73	0,012
	27	3	297	0,049	83	0,013
	28	3,5	252	0,042	56	0,009
	31	4,9	298	0,049	62	0,01
	34	3,2	176	0,029	62	0,01
	35	3,5	399	0,066	139	0,023
	36	5,1	478	0,079	62	0,01
	36	4,2	391	0,065	85	0,014
	37	5,7	483	0,08	170	0,028
	37	3,7	435	0,072	215	0,035
	37	3,5	340	0,056	92	0,015
	37	6	416	0,069	67	0,011
	40	3,6	135	0,022	85	0,014
	40	7,4	436	0,072	142	0,023
	41	6,7	460	0,076	143	0,023
	43	4,4	424	0,07	177	0,029
	43	3,6	374	0,062	57	0,009
	44	5	367	0,061	159	0,026
	44	3,9	345	0,057	151	0,025
	45	4,3	344	0,057	173	0,028
	46	3,2	121	0,02	65	0,01
	46	6,4	237	0,039	147	0,024
	46	4,9	266	0,044	65	0,01
	47	3,5	313	0,052	80	0,013
	50	12	215	0,035	85	0,014
	50	4,4	275	0,045	54	0,009
	50	5	409	0,068	127	0,021
	50	8,7	447	0,074	61	0,01
	51	9,5	244	0,04	79	0,013

	52	6,8	400	0,066	162	0,027
	54	4,6	482	0,08	239	0,039
	54	6,9	416	0,069	196	0,032
	54	3	415	0,069	180	0,03
	54	6	253	0,042	112	0,018
	55	3,5	360	0,06	62	0,01
	57	5,8	215	0,035	125	0,02
	57	6,7	376	0,062	181	0,03
	59	5,9	456	0,076	105	0,017
	60	5,4	448	0,074	190	0,031
	60	4,7	438	0,073	52	0,008
	61	8,6	439	0,073	170	0,028
	62	6	136	0,022	79	0,013
	62	5,9	452	0,075	178	0,029
	63	6	450	0,075	203	0,033
	64	6,9	444	0,074	141	0,023
	65	6,5	411	0,068	52	0,008

Relevant Statistical Terms:

C**onfidence interval -** gives an estimated range of values which is likely to include an unknown population parameter, the estimated range being calculated from a given set of sample data.

Confidence level - the probability, expressed as a percentage, that a confidence interval encloses the population parameter (We can be 95% confident that this interval encloses the actual population parameter.).

Continuous variable - a variable that can assume values corresponding to any of the points contained in one or more intervals (e.g. height, weight, time).

Correlation - a relationship between 2 variables.

Dependent or response variable - a variable of interest to be measured in an experiment, we usually are interested in determining the effect of one or more independent variables on the response variable.

Independent variable - a predictor variable, one which is not being affected by other variables in the experiment (e.g. age or frequency in our experiments).

Mean - the sum of the measurements divided by the number of measurement contained in the data set (average).

Median - the middle number when the measurements are arranged in ascending or descending order.

Null hypothesis - the hypothesis that is being falsified by a specified statistical test (usually that the values being tested are equal).

Prediction interval - is an estimate of an interval in which future observations will fall, with a certain probability, given what has already been observed.

Standard deviation - the square root of the variance.

Statistic - a number calculated from a sample of observed data to make an inference about the population to which the sample belongs.

Statistically significant - implies that you have used statistical methods, which account for means and variances, to conclude that your measurements for different populations or treatments are different.

Statistics - the science of data – collecting, classifying, summarizing, organizing, analyzing, and interpreting numerical information

Appendix 2. Model

Model design and structure

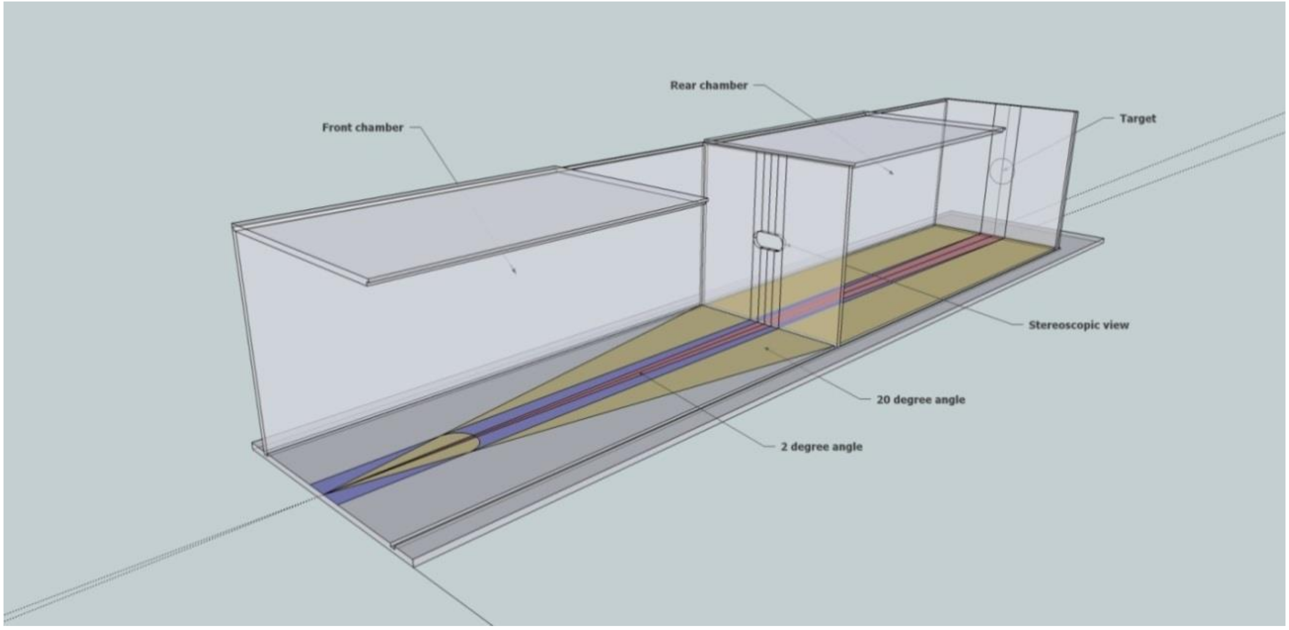


Fig.8: An overview of the testing model showing the structure. Colors on the base surface do not exist in reality; they are here representing the design logic.


Fig.9 and 10: Show the target on the back surface (2x2x2mm) and the steroscopic opening in the middle surface.


Fig.11 and 12: Showing both surfaces in model and the reflectance of the background (left –gray) and foreground (right – white).

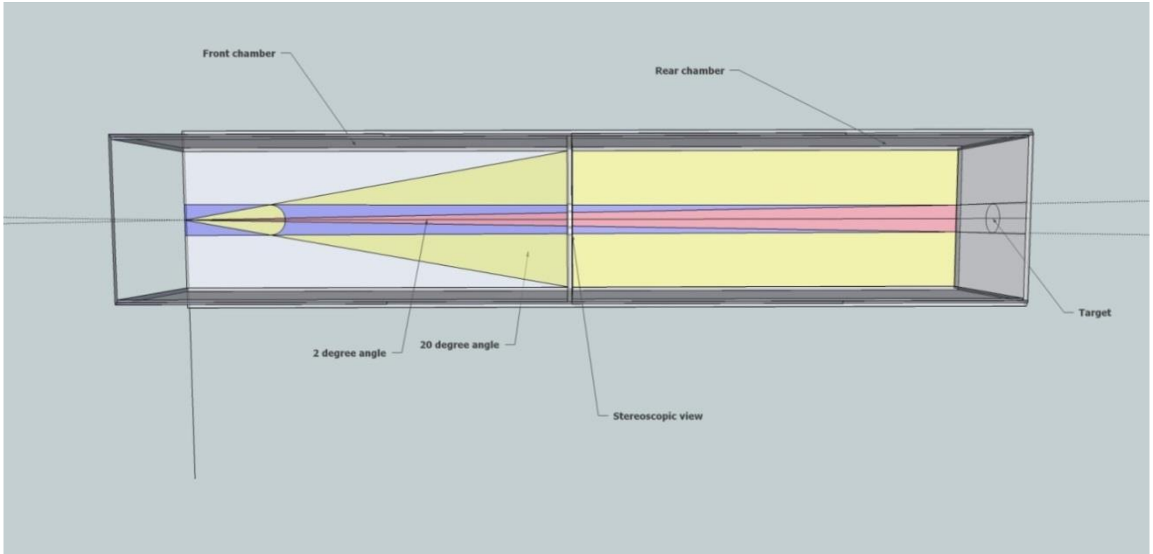


Fig.13: Top view showing the point of view (left to right) and the directional guidelines for the construction of the testing model.

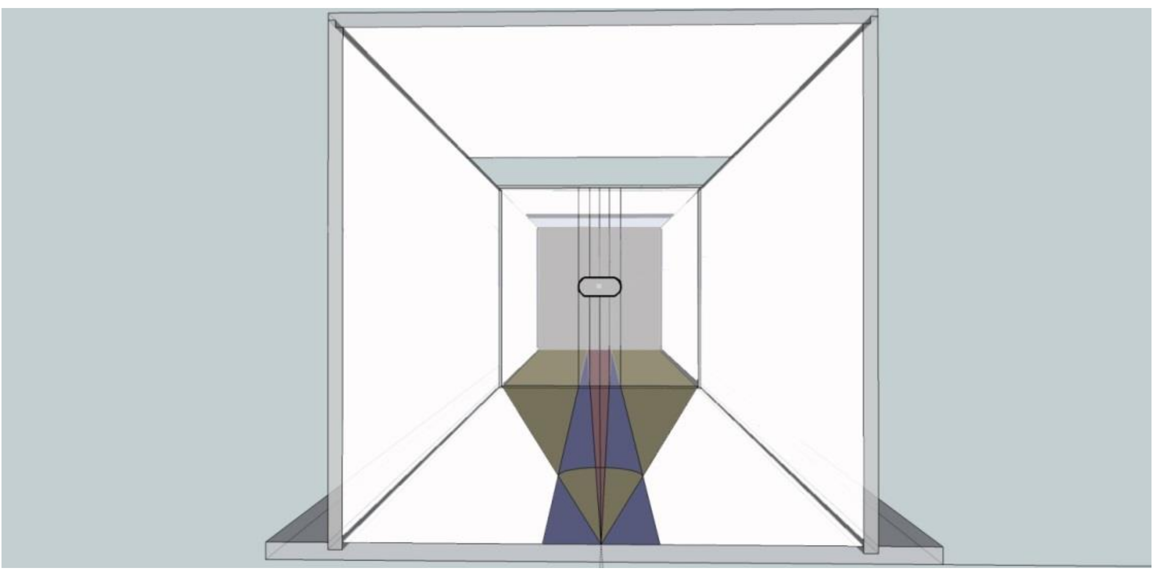
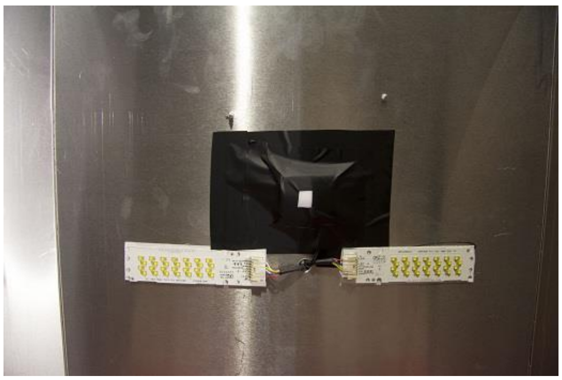


Fig.14: Front view, as will be seen from user point of view.

Fig.15 (1-3): Three lighting situations. To the left – front chamber fully lit (target is invisible). Middle showing equal (low) light levels in both chambers (target appears). Right hand showing dark front chamber and back chamber lit (target clearly visible).

Fig.16 and 17: The custom made lighting structures. These fixtures mount on top of the model structure in the gap left open for them. The prevent external light spill and act as additional heat sinks.



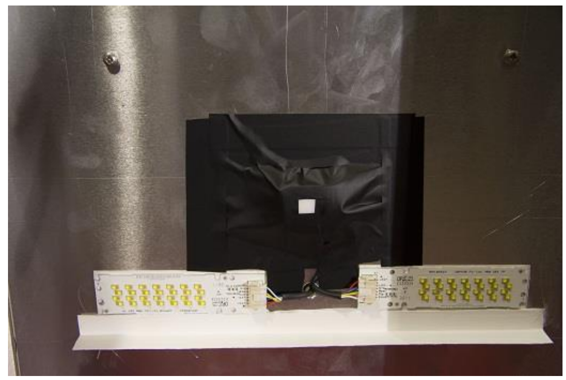


Fig.18 and 19: Both fixtures are equipped with 2x Philips *Fortimo LED high brightness* modules capable of reaching levels of 12,000cd/m^2 (L_{seq} and L_{th}) and one small LED source to reach low light levels as in the tunnel interior (L_{in}). The module on the right hand side is the one to fit in the front chamber where the user looks in; therefore it is equipped with an anti-glare reflector.

Fig.20: Xitanium 150W Programmable LED driver for the *Fortimo* drivers (one for every fixture). Fig.21: *Xitanium LED Driver 10W/0.70A-14V DIM* for the small LED.

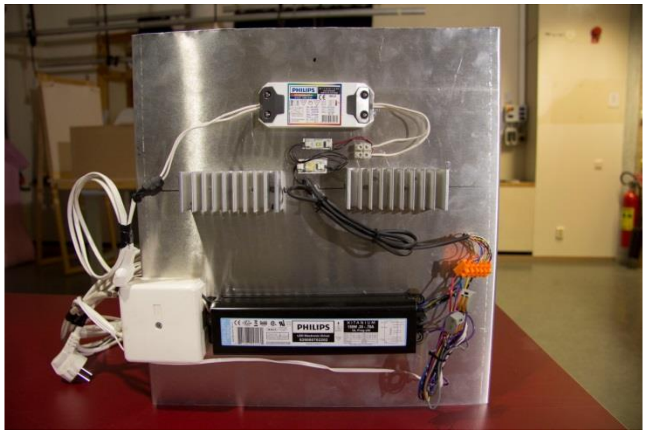


Fig.22: Top view of a complete module. Wiring and heat sinks exposed for easy control and better ventilation.

Construction

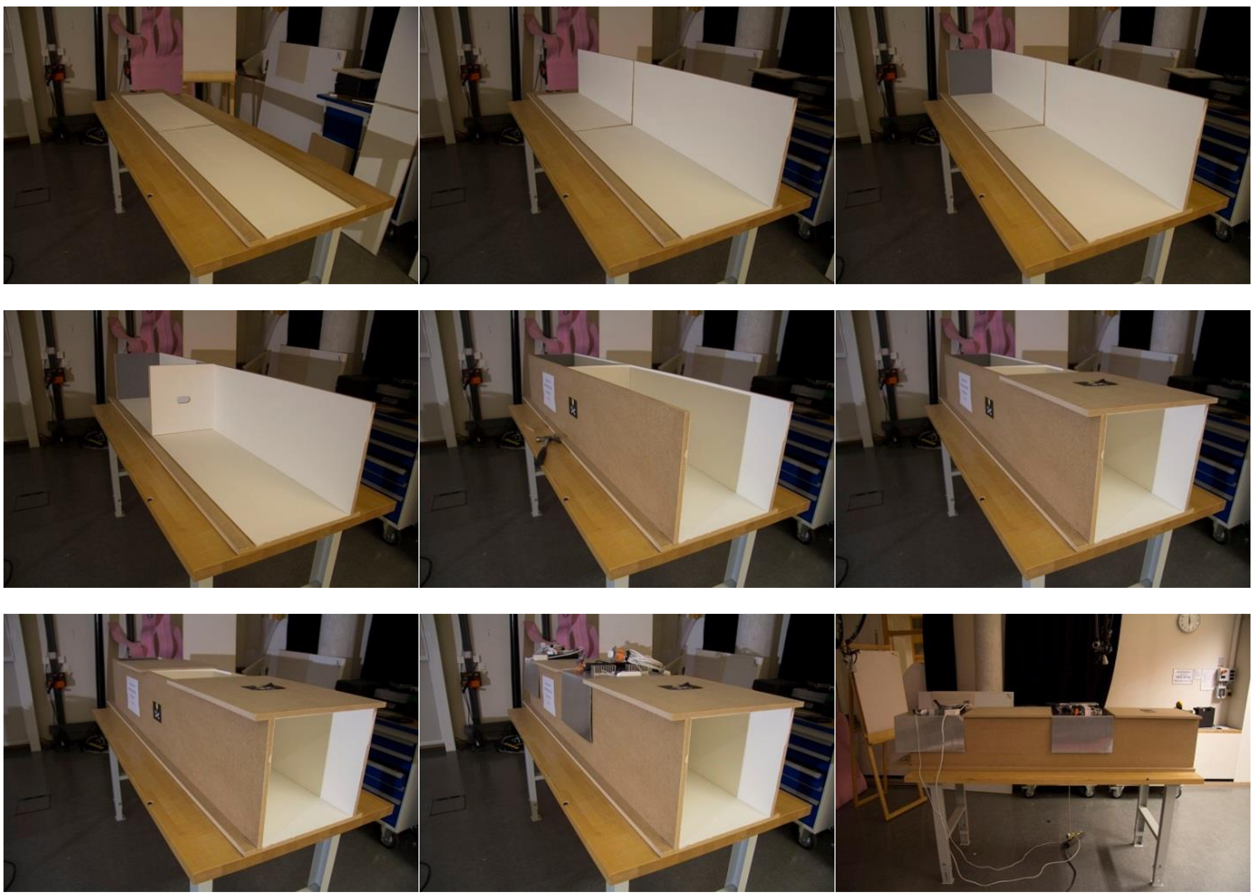


Fig.23 (1-9): All body parts (made of MDF) are connected by sliding grooves and the structure is designed to hold its own form and strength. The lighting fixtures simply sit on top where the openings are situated.

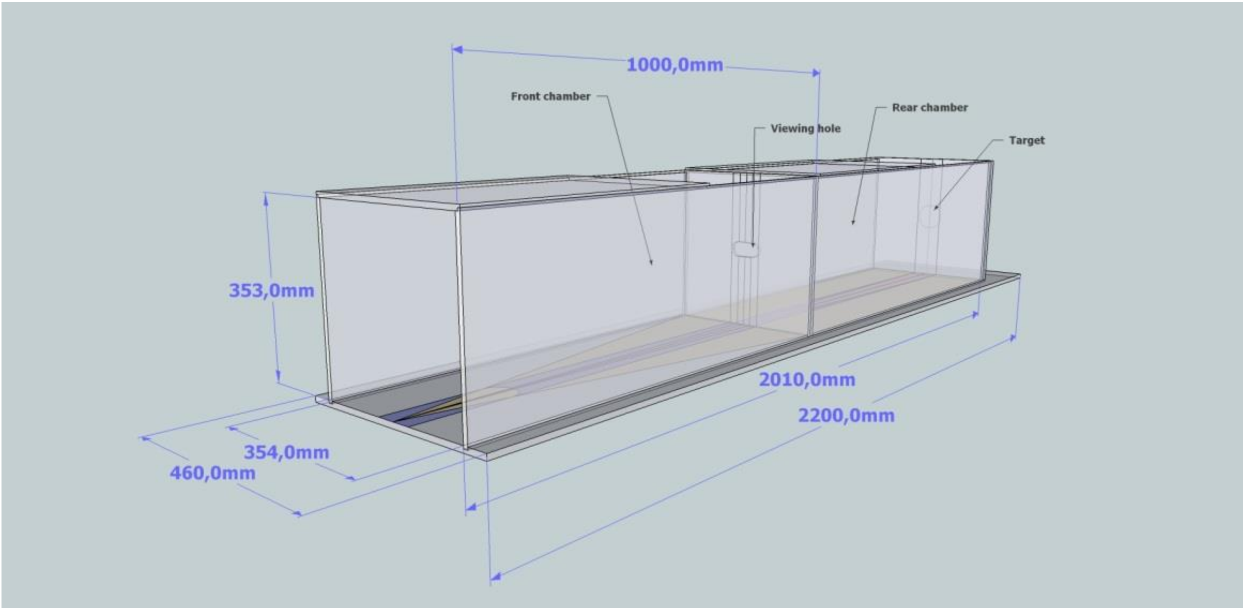


Fig.24: Measurements.

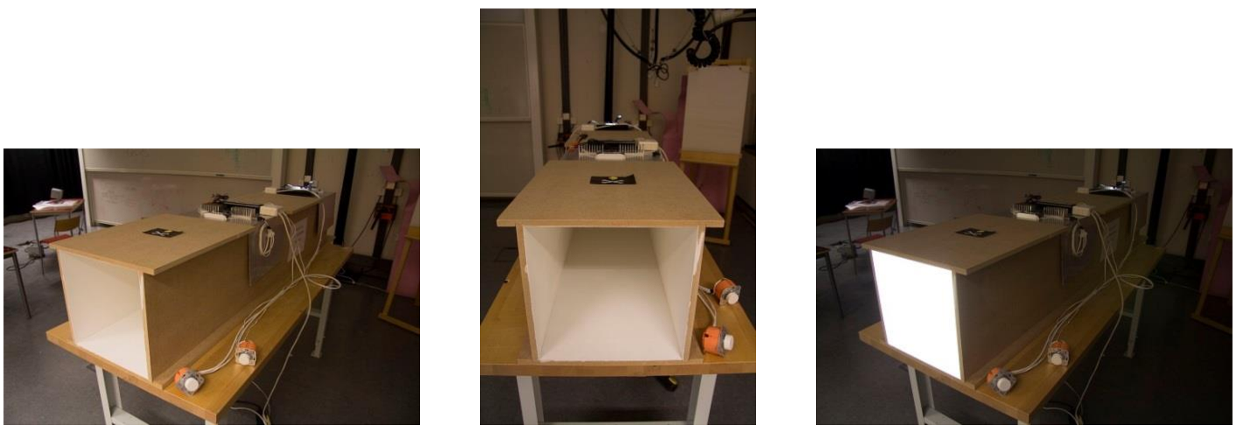


Fig. 25 (1-3): The control system for dimming and switching the lights on-off is shown here to the right hand side of the model. It is to be primarily controlled by the operator to determine the required light levels. All interior surfaces are painted white to maximize the reflectance. The back surface (with the target on) is the only one painted in grey (lightness value of 0.5, NCS), that is for reaching easily the contrast of 20% with the target.

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- Statistical terms: http://www.monarchlab.org/Lab/Research/Stats/Terms.aspx
- Besides figures 1, 2 and 3, all other graphical material presented in this paper was created by the author.
- Statistical graphs were done by Dr. Elias Said using "MINITAB" software.

- "Visual adaptation for tunnel entrance" is the second research the lighting laboratory at KTH-STH had conducted for Trafikverket – the Swedish Road Administration. Preceding this research and during most of 2012 a research called "Lighting Häggvik Tunnel, Sollentuna" took place. The complete research paper can be found at: http://kth.divaportal.org/smash/get/diva2:601695/FULLTEXT01.pdf

Eran Aronson.

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The Lighting Laboratory, KTH STH, Sweden.