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Carbon Management: A New Dimension of Future Carbon Research

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Contents

Abstract

This paper investigates the role of uncertainties in verifying the Kyoto Protocol. A verification time concept that has been developed at IIASA is applied to higher-order Taylor expansions to describe emission signals. Verification times for Annex I countries, depending on the dynamics of emissions and associated uncertainties, are analyzed up to the second-order.

Acknowledgments

We would like to thank Matthias Jonas of the Forestry Project, who was our supervisor during the summer of 2000, for the useful discussions, comments, and guidance with this study as well as his help in finalizing this paper. We are also grateful to Shari Jandl for her editorial assistance, and all the Forestry team for their support in this research. Margaret Traber, YSSP coordinator, and IIASA staff did everything possible to make our stay at IIASA pleasurable.

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About the Authors

Mykola Gusti graduated from the Lviv Franko National University in 1996, where he completed his Diploma Thesis on Macromodels with Chebyshev approximation in the field of radiophysics. After graduation, he worked as an engineer in the Department of Complex Dynamical Systems Modeling at the Research Institute of Information Infrastructure in Lviv, Ukraine. In 1997, he became a Ph.D. student at the same institute. In 2001, he defended his Ph.D. thesis on Modeling the Dynamics of the Carbon Budget of Ecosystems of the Carpathian Region in Ukraine. In support of his Ph.D. work, Mykola was granted a two-month fellowship by the Austrian Federal Ministry of Science and Transport, which he spent at IIASA in the fall of 1999. His scientific interests are mathematical modeling and data processing applicable in environment research.

In the summer of 2000, he was a participant in IIASA's Young Scientists Summer Program (YSSP) affiliated with the Forestry Project, participating in the project's carbon research related to the Kyoto Protocol. His task during the summer was to scrutinize the verification time concept formulated by Jonas *et al*. (1999) and to calculate verification times for the Annex I countries under the Protocol.

Waldemar Jęda earned his masters degree from the Faculty of Applied Physics and Mathematics at the Warsaw University of Technology. After graduation, he continued his postgraduate work at the Faculty of Physics (WUT) and at the Graduate School for Social Research of the Polish Academy of Sciences. At the beginning of 2000, he received his doctorate in physics.

Since the beginning of 1999, Waldemar has been a research associate in the Laboratory of Computer Modeling and Identification at the Systems Research Institute of the Polish Academy of Sciences. He is currently studying methodologies for constructing biological, medical, economic, and technical models in consideration of uncertainty.

In the summer of 2000, he was a participant in IIASA's Young Scientists Summer Program (YSSP) affiliated with the Forestry Project, participating in the project's carbon research related to the Kyoto Protocol. His task during the summer was to investigate the issue of the smoothness of emission scenarios and the consequences of calculating verification times.

Carbon Management: A New Dimension of Future Carbon Research

Mykola Gusti and Waldemar Jęda

1 Introduction

The Kyoto Protocol to the United Nations Framework Convention on Climate Change (UNFCCC, 1997), which was adopted by the Conference of the Parties at its third meeting in 1997, is mankind's reaction to the climate change problem. The Protocol is supposed to be a measure to deal with this problem. The Protocol defines commitments for countries (developed countries and countries with economies in transition) listed in the Convention's Annex I (*Annex I countries*), to reduce (or limit) greenhouse gas emissions to certain levels compared to a specified base year (quantified emission limitations or reduction commitments is 5.2% on average) during 2008–2012 (first *Kyoto commitment period*). The Protocol left many issues unresolved. This resulted in many questions arising and a new wave of carbon related studies being instigated.

Uncertain emission estimates and their verification are one of the problems that the Kyoto Protocol must cope with during its implementation. As a matter of fact, this particular problem is shunted aside as a "technical matter" in the Kyoto policy process. However, the scientific basis of how to deal with uncertainty and verification under the Protocol is fundamentally unclear.

The problem is that in most cases the uncertainties in emission estimates are greater than the reductions or limitations on which the Annex I countries have agreed to reduce or limit their emissions according to the Kyoto Protocol. Thus, there is a situation where it is impossible to verify whether an Annex I country has complied with its commitment (e.g., reduced emissions to a certain level), or even whether the country is approaching the commitment (e.g., is reducing the emissions). Verification time (VT), introduced by Jonas *et al*. (1999), can help answer the question: When could change in emissions be measured with certainty?

Many works are devoted to the assessment and management of uncertainties in emission estimates (e.g., EIIP, 1997; IPCC/OECD/IEA, 1997; 1998; Charles *et al*., 1998; IPCC, 2000; Rypdal and Zhang, 2000). The Intergovernmental Panel on Climate Change (IPCC) recognizes that uncertainties in emissions estimates can affect the Kyoto Protocol. The IPCC/OECD/IEA (1998:5) states:

> "…*Also, the prospect of using flexible mechanisms, including emissions trading, means that Parties will have even greater interest in the reliability of other national inventories.*

In Kyoto, the Parties recognized that greenhouse gas inventories are uncertain, and that unless uncertainties are reduced and managed, there is a risk that Parties could adjust their emissions estimates within the band of uncertainty to help them "meet" their commitments, introducing bias into the emissions estimates."

According to IPCC (2000:1.4):

> *"…the overall uncertainty in emissions estimates weighted by global warming potentials (GWPs) in a single year could be of the order of 20%* [95% confidence interval][1]*, mainly due to uncertainties in non-CO_2 gases.*
>
> *…the uncertainty in the trend of emissions may be less than the uncertainty in the absolute value of emissions in any year. This is because a method that over or underestimates emissions from a source category in one year may similarly over or underestimate emissions in subsequent years"* (also in IPCC/OECD/IEA, 1998:13; Charles *et al*., 1998).

Jonas *et al*. (1999) and Obersteiner *et al*. (2000) studied in greater depth how overall or level uncertainties and trend uncertainties can influence the Protocol.

In this study, we only deal with the level uncertainties (not trend uncertainties), which we assume, for the purpose of this work, do not depend directly on the emissions themselves. We consider CO_2 emissions from fossil fuel burning, gas flaring, and cement production (what we call the fossil fuel or FF system) for the following reasons:

- Carbon dioxide is the most important anthropogenic greenhouse gas;
- CO_2 emissions from fossil fuel burning and cement production are responsible for more than 70% of all anthropogenic CO_2 emissions;
- CO_2 emissions from fossil fuel burning and cement production are known for many countries (and for most Annex I countries) for quite a long time period, which allows to investigate the emission dynamics of the FF system more reliably; and
- CO_2 emissions are considered to reveal the lowest uncertainty.

In this study we tried to answer the following questions:

- What are the verification conditions under which Annex I countries are currently operating (business-as-usual case)?
- Is it realistic for the Annex I countries to reach their Kyoto targets during the Kyoto commitment period?
- Can Annex I countries verify their emissions changes?

In Section 2, we introduce definitions and the problem of uncertainties in emission estimates in general. In Sections 3 and 4, we develop a VT concept of higher-order Taylor expansions and apply it for calculations of the VT of FF CO_2 emissions for Annex I countries. We also study the problem of whether the Kyoto targets can be reached. Details of the calculations are presented in the Appendix.

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[1] Authors' comment.

2 Verification Time (VT) Concept

We start with the introduction of the VT concept, which was formulated by Jonas *et al*. (1999:10):

> *"…what we consider a reasonable standard condition for verification. This condition states that the absolute change in the country's net carbon emissions,* ($|\Delta F_{net}(t_2)|$) *at time* t_2*, with respect to time* t_1 ($t_1 < t_2$)*, is greater than the uncertainty in the reported net carbon emissions at time* t_2*. This condition permits favorable verification, that is, verification that is compatible with the reported change in net carbon emissions:*
>
> $$|\Delta F_{net}(t_2)| > \varepsilon(t_2) \;, \qquad (1.1)$$
>
> *or under the non-restrictive assumption that first-order (i.e., linear) approximations are applicable,*
>
> $$\left|\frac{dF_{net}}{dt}\right|_{t_1} \Delta t > \varepsilon(t_2) \qquad (1.2)\ldots"$$

In Figure 1, the change in net emissions (F) cannot be verified in time t'_2 because $F(t'_2) - F(t_1) < \varepsilon(t'_2)$ and, correspondingly, reaching the reduction target (star) can also not be verified. The change in emissions can be verified only after t_2, when $F(t_2) - F(t_1) \geq \varepsilon(t_2)$.

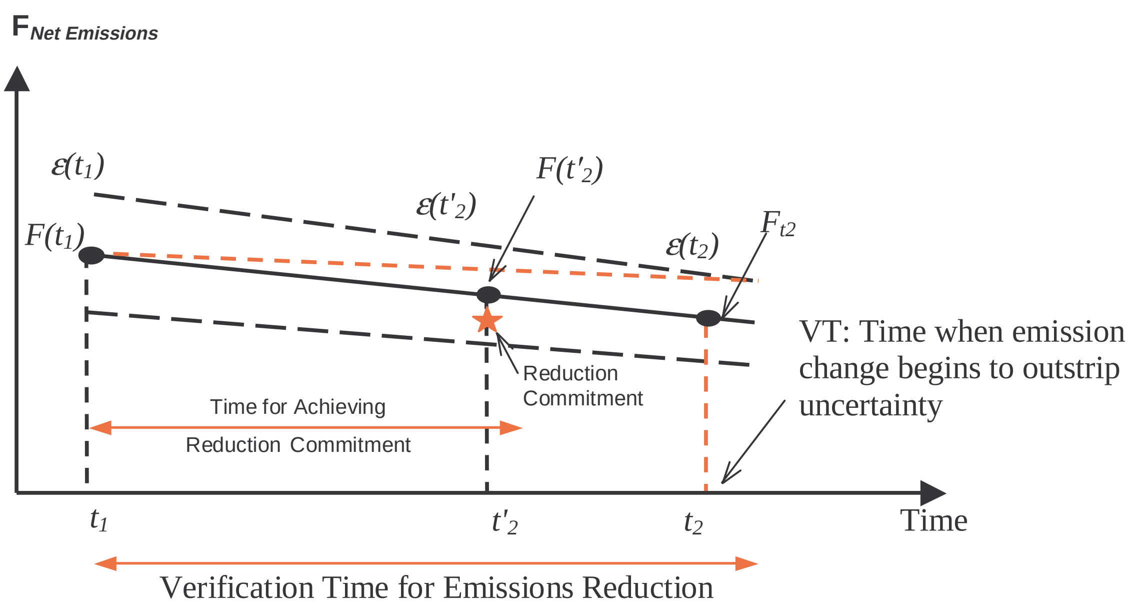


Figure 1: Illustration of the verification time concept.
Source: Modified from Jonas (2000a,b).

Thus, we are searching for the time after which the absolute change in net emissions outstrips uncertainty. This time is called verification time (VT) and the associated uncertainty is called the critical uncertainty:

$$\left|\Delta F_{net}(t)\right| > \varepsilon(t) \ , \tag{1.3}$$

To solve equation (1.3), we describe the emission data by a n^{th}-order polynomial (using the least squares technique) and the uncertainty by a first-order polynomial, assuming (without restricting generality) that the uncertainty can be reduced in future due to increased knowledge, and improved methodologies and measurements. We use Taylor expansions for the polynomials. Taking the above-mentioned into account, we can rewrite equation (1.3) in the following general form:

$$\left|\sum_n \frac{1}{n!} \frac{d^{(n)}F}{dt^n}\right|_{t_0} (t-t_0)^n \left| > \varepsilon(t_0) + \frac{d\varepsilon}{dt}\right|_{t_0} (t-t_0) \ . \tag{1.4}$$

Equation (1.4) is solved for t-t_0 after which the absolute change in emissions outstrips the uncertainty.

In the case that both emissions and uncertainty can be fitted to a first-order polynomial, equation (1.4) reduces to:

$$\left|\frac{dF}{dt}\right|_{t_0} (t-t_0) \left| > \varepsilon(t_0) + \frac{d\varepsilon}{dt}\right|_{t_0} (t-t_0) \ . \tag{1.5}$$

Equation (1.5) is illustrated in Figure 2. If uncertainty is reduced ($\left.\frac{d\varepsilon}{dt}\right|_{t_0} < 0$) the VT is less than if the uncertainty is constant ($\left.\frac{d\varepsilon}{dt}\right|_{t_0} = 0$) or, moreover, if it is increasing ($\left.\frac{d\varepsilon}{dt}\right|_{t_0} > 0$).

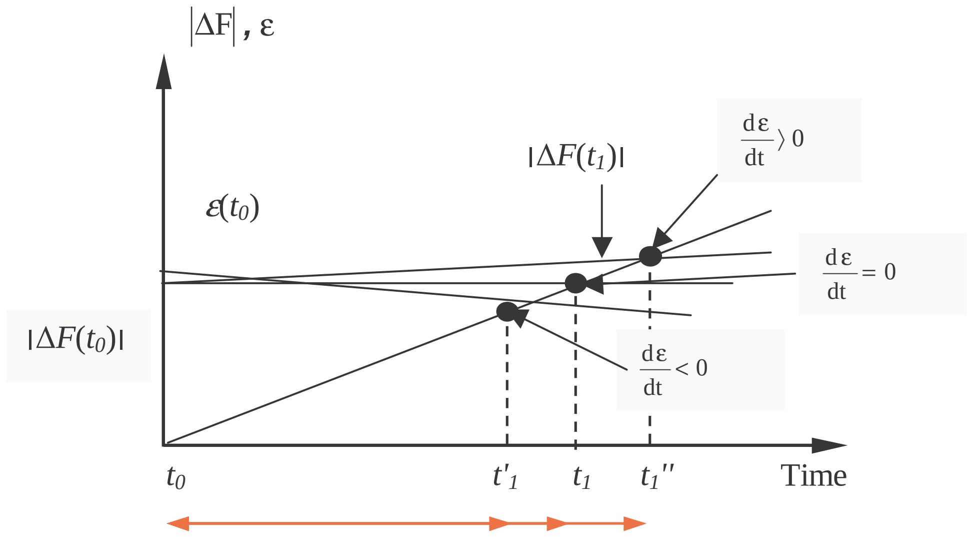


Figure 2: Illustration of equation (1.5). Hence, $|\Delta F|$ denotes the net emissions change and ε the associated uncertainty. $|\Delta F|$ and ε are described by first-order polynomials.

In the case that emission data can be fitted to a second-order polynomial (and uncertainty to a first-order polynomial, as before), we rewrite equation (1.4) as follows:

$$\left| \left.\frac{dF}{dt}\right|_{t_0} (t - t_0) + \frac{1}{2} \left.\frac{d^2F}{dt^2}\right|_{t_0} (t - t_0)^2 \right| > \varepsilon(t_0) + \left.\frac{d\varepsilon}{dt}\right|_{t_0} (t - t_0) \,. \tag{1.6}$$

As in the previous case, equation (1.6) is illustrated in Figure 3. If uncertainty is reduced ($\left.\frac{d\varepsilon}{dt}\right|_{t_0} < 0$) the VT is less than if the uncertainty is constant ($\left.\frac{d\varepsilon}{dt}\right|_{t_0} = 0$) or, moreover, if it is increasing ($\left.\frac{d\varepsilon}{dt}\right|_{t_0} > 0$).

The solutions are obtained in explicit form and analyzed in further sections.

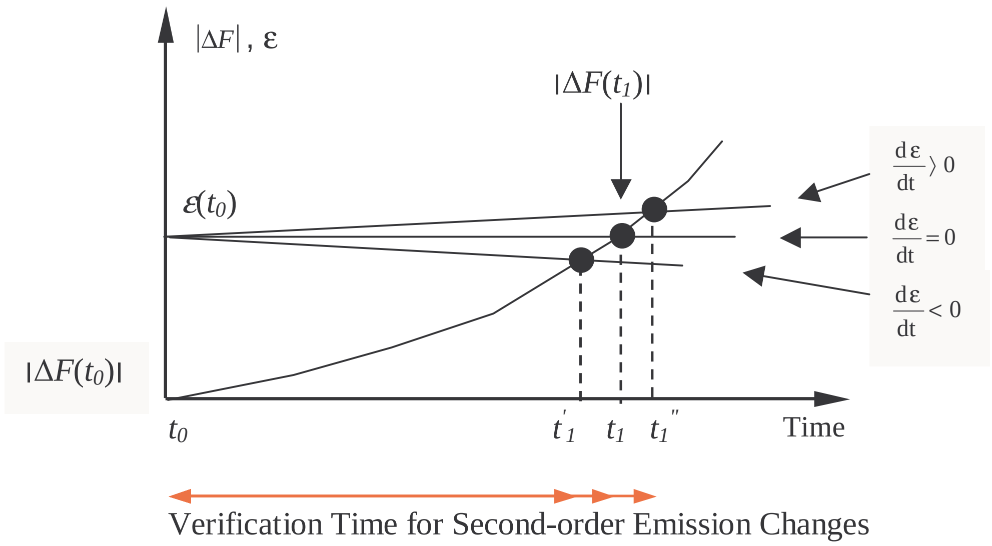


Figure 3: Illustration of equation (1.6). Hence, $|\Delta F|$ denotes the net emissions change and ε the associated uncertainty. $|\Delta F|$ is described by a second-order polynomial and ε by a first-order polynomial (as before).

3 VT and Reachability of the Kyoto Targets for Annex I Countries

3.1 Data and Assumptions Used

In Section 3.2, we only use information about Kyoto commitments of the Annex I countries, presented in the Kyoto Protocol (UNFCCC, 1997), to show that a comparison of emissions in two years is not valid, because the emission uncertainties are greater than the amount that the emissions must be changed.

One of the tasks of this part of the work (Section 3.3) is to reveal what can we learn about verification conditions of Annex I countries from the short emission data series contained in the UNFCCC database (UNFCCC, 2000) (at the time of writing, for most Annex I countries data is available for 1990–1996). As the emissions reported by the countries are not well harmonized and we need a long data series for studying the physical features, we used the Marland *et al*. (1999a) database for the calculations. This database was chosen because it contains data of CO_2 emissions from fossil fuel burning cement production and gas flaring (FF system) for most of the Annex I countries, covers a long period of time, and treats all countries in the same way. For some countries the data dates back to 1751. The estimates of CO_2 emissions from fossil fuel burning are derived from United Nations (UN) energy statistics and calculated using the methods of Marland and Rotty (1984). The estimates of CO_2 emissions from cement production are derived from the data of the United States (US) Department of Interior Bureau of Mines. The estimates of CO_2 emissions from gas flaring are derived from UN data, supplemented with data from the US Department Energy Information Administration and national estimates provided by Marland *et al*. (1999a). As Marland *et al*. (1999b) and Marland (2000) pointed out, their emission estimates are sensitive to initial data and methods used for the emission calculations. For the VT calculations we only used a limited amount of data (for 1990–1996) to imitate UNFCCC database conditions (Section 3.3), and all available data for studying the physical properties of countries' FF systems (Section 3.4).

In Section 3.2, the VT calculations are done for the "business-as-usual" case because we used data emission values before 1997, when the Kyoto Protocol was adopted. Thus, the emissions are not affected by the Protocol.

According to Marland (2000), the uncertainty of global emissions is more than 10% before 1950, about 10% after 1950, and has not been significantly reduced thereafter. Uncertainties in national estimates are smaller or greater. According to IPCC/OECD/IEA (1997:16), the uncertainty of CO_2 emission estimates presented in greenhouse gas (GHG) inventories in the energy sector is less than 10%, in the industrial processes sector it is about 15%, and the overall uncertainty in emission estimates reported to the IPCC are about 20% (IPCC, 2000:1.4). So we assumed a 10% uncertainty for all Annex I countries for base calculations and a range of 2.5%–20% for the additional calculations.

First, we describe the uncertainty in emission estimates in absolute terms following Jonas *et al*. (1999). Since the countries to the Kyoto Protocol report uncertainties in relative units, we use this value to calculate the absolute uncertainty at a specific point in time. Usually, this is the midpoint of the dataset, e.g., if there is data for 1990, 1991, 1992,…,1996, then the central point corresponds to the emission level in 1993. However, for some countries data is only available since 1992, then the central point corresponds to 1994[2]. Second, we use the relative uncertainties for the VT calculations directly, because the uncertainties are generally reported in relative terms in practice. In this case, uncertainties "follow" the data at each point of time and the VT calculations are modified accordingly (see Section 3.3.3).

We assume, without restricting generality, that uncertainty can be reduced in future because of increased knowledge, improved measurements, statistics, and methodologies, etc. However, uncertainties can also increase (e.g., if they are described in relative terms and linked to increasing emissions).

We do not consider net emissions from land-use change and forestry (LUCF) activities because (at the time of writing) it is not yet clear which activities will eventually be permitted under the Kyoto Protocol. Uncertainty of the CO_2 sink, due to biomass increment, must be expected to be greater than 25% (IPCC/OECD/IEA, 1997:16), which can make verification conditions only worse.

Here, we use the term "uncertainty" both for the deviation of mean value (e.g., $M \pm m$) with respect to a certain confidence interval if the uncertainty is quantified, and as in the

[2] For countries where data is only available since 1992, the central point is 1994 not 1993, and the starting year is 1992 not 1990.

IPCC (2000:A3.18): "*…general and imprecise term which refers to the lack of certainty resulting from any casual factor such as unidentified sources and sinks, lack of transparency, etc.*" if it is not quantified.

In mathematical expressions, we use F for emissions, R for uncertainty in relative terms, and ε for uncertainty in absolute terms. All calculations are done using Matlab 5.2.

3.2 Critical Relative Uncertainty

3.2.1 Methodology

F_{t_1} are a country's net GHG emissions in base year t_1 (1990 for most of the Annex I countries). The country may have to change its emissions to $k*100\%$ in the commitment year t_2 (here, 2010, the midpoint of the Kyoto commitment period). Thus, a country's net emissions in t_2 should be equal to $F_{t2}=k*F_{t1}$ in 2010 (Figure 4).

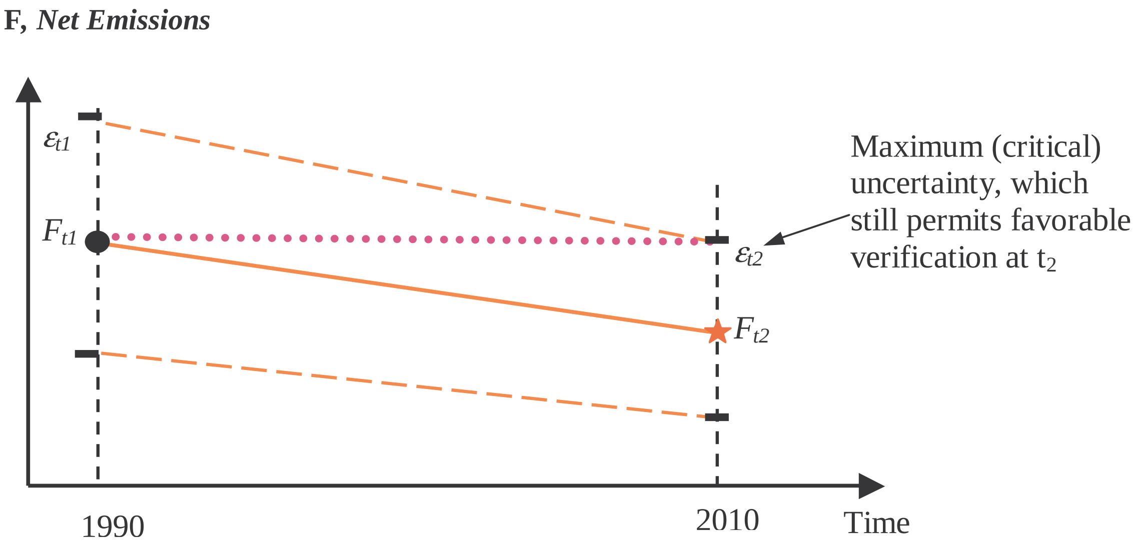


Figure 4: Illustration of the critical uncertainty concept. Here, ε_1 is absolute uncertainty in base year t_1 (e.g., 1990) and ε_2 is absolute uncertainty in commitment year t_2 (2010).

Assuming initially that the relative uncertainty of the emissions stays constant over time, i.e.,

$$R = \frac{\varepsilon_1}{F_{t_1}} = \frac{\varepsilon_2}{F_{t_2}} = const, \qquad (3.1a,b)$$

and relating the emissions at t_1 and t_2 via:

$$\frac{F_{t_2}}{F_{t_1}} = k \qquad (3.2)$$

(k is defined for each Annex I country by the Kyoto Protocol), we find for the critical relative uncertainty at t_2:

$$\varepsilon_2 = \varepsilon_1 * \frac{F_{t_2}}{F_{t_1}} = \varepsilon_1 * k\,. \qquad (3.3a,b)$$

In order to verify the change in emissions, it must be greater than the absolute uncertainty at time t_2:

$$abs\left(F_{t_1} - F_{t_2}\right) > \varepsilon_2\,. \qquad (3.4)$$

Substituting for F_{t_2} and ε_2, we find:

Case $F_{t_1} > F_{t_2}$:

$$\left(F_{t_1} - k * F_{t_1}\right) > k * \varepsilon_1\,. \qquad (3.5)$$

Thus:

$$\frac{(1-k)}{k} > \frac{\varepsilon_1}{F_{t_1}}, \qquad (3.6)$$

meaning that emission changes can only be measured (verified) if the relative uncertainty of the emissions at t_2, R, is less than the critical relative uncertainty R_{crit}:

$$R_{crit} = \frac{(1-k)}{k}\,. \qquad (3.7)$$

Case $F_{t_1} < F_{t_2}$: In the case of increasing emissions ($F_{t_1} < F_{t_2}$), $R < R_{crit}$ where equation (3.7) changes to:

$$R_{crit} = \frac{(k-1)}{k}\,. \qquad (3.8)$$

3.2.2 Results and discussion

In order for changes in emissions to be verifiable (measurable), the relative uncertainty of the emission estimates must be less than the critical relative uncertainty. For the calculations, we used the data presented in Annex 3 of the Kyoto Protocol about Kyoto commitments of the countries. The critical relative uncertainty (column 3 of Table 1) is calculated using equation (3.7) or (3.8).

Table 1: Critical relative uncertainty for Annex I countries.

Country	**Quantified emission limitation (positive) or reduction commitment (negative) %**	**Critical relative uncertainty R_{crit}, %**
Australia	+8	7.4
Austria	-8	8.7
Belgium	-8	8.7
Bulgaria	-8	8.7
Canada	-6	6.4
Croatia	-5	5.3
Czech Republic	-8	8.7
Denmark	-8	8.7
Estonia	-8	8.7
European Community	-8	8.7
Finland	-8	8.7
France	-8	8.7
Germany	-8	8.7
Greece	-8	8.7
Hungary	-6	6.4
Iceland	+10	9.1
Ireland	-8	8.7
Italy	-8	8.7
Japan	-6	6.4
Latvia	-8	8.7
Liechtenstein	-8	8.7
Lithuania	-8	8.7
Luxembourg	-8	8.7
Monaco	-8	8.7
Netherlands	-8	8.7
New Zealand	0	0
Norway	+1	1
Poland	-6	6.4
Portugal	-8	8.7
Romania	-8	8.7
Russian Federation	0	0
Slovakia	-8	8.7
Slovenia	-8	8.7
Spain	-8	8.7
Sweden	-8	8.7
Switzerland	-8	8.7
Ukraine	0	0
UK	-8	8.7
USA	-7	7.5

According to the IPCC (2000:1.4), the overall (level) uncertainty of emissions is about 20% (95% confidence interval). Thus, none of the Annex I Parties could verify the change in their emissions and thereby reach their Kyoto targets (Table 1). If the concept of trend uncertainty is used, which can be expected to be in the order of 5% (Charles *et al*., 1998; IPCC/OECD/IEA, 1998; IPCC, 2000; Rypdal and Zhang, 2000), then most of the Annex I Parties could potentially verify the changes of their emissions. There are some countries that must freeze their emissions of greenhouse gases on their base year levels (New Zealand, Russian Federation, and Ukraine) or change the emissions by a small value (Norway). For these countries, it is impossible to verify the change in emissions in both cases when we apply the concept of level uncertainty or trend uncertainty, because critical relative uncertainty for their emission estimates is less than 5%. Thus we must take into account the dynamics of the emissions, which is mentioned by the VT concept and considered in further sections.

3.3 VT Calculations

3.3.1 Methodology for first-order approach in consideration of absolute uncertainty

The methodology mentioned below takes into account the dynamics of emission changes.

We must find time *t*, which satisfies the relation:

$$\left|F(t)-F(t_0)\right|>\varepsilon(t),\quad t>t_0\,, \tag{3.9}$$

where *F(t)* are the emission estimates (FF emissions data fitted by a polynomial), $\varepsilon(t)$ is the absolute uncertainty, and t_0 the base year (central point, see Section 3.1).

We begin by calculating the VT for Annex I countries using the first-order approach to describe both the change in emissions and the associated absolute uncertainty (Jonas *et al*., 1999). The emissions are taken from Marland *et al*.'s (1999a) data and cover the years 1990 (or 1992) to 1996 (see Section 3.1). Their linear regression enables us to find the first derivative and apply the formula (Jonas *et al*., 1999):

$$t>\frac{\varepsilon(t_0)}{\left|\frac{dF}{dt}\right|_{t_0}-\left(\frac{d\varepsilon}{dt}\right)_{t_0}}\,, \tag{3.10}$$

where $\left|\frac{dF}{dt}\right|_{t_0}>\left(\frac{d\varepsilon}{dt}\right)_{t_0}$.

Figures 5 and 6 depict Austria as an example. The linearly fitted emission (FF) data are shown in Figure 5, while their associated VT, in accordance with equation (3.10), is shown in Figure 6 for various initial assumptions of $\varepsilon(t_0)$ (t_0 = 1993).

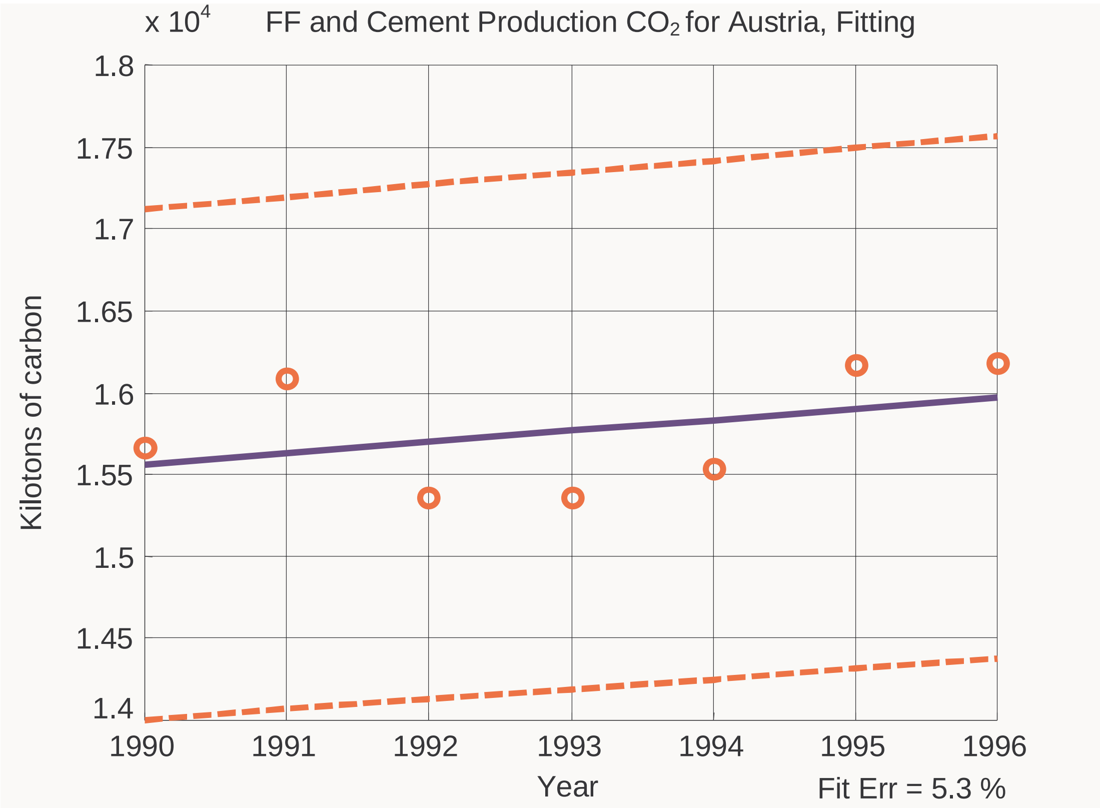


Figure 5: Austria's FF emissions for 1990–1996 and their linear regression. The red lines correspond to ±10% boundaries around the regression, Fit Err is calculated as the square root of the sum of squares of the differences between data and regression relative to the emission level in 1990.

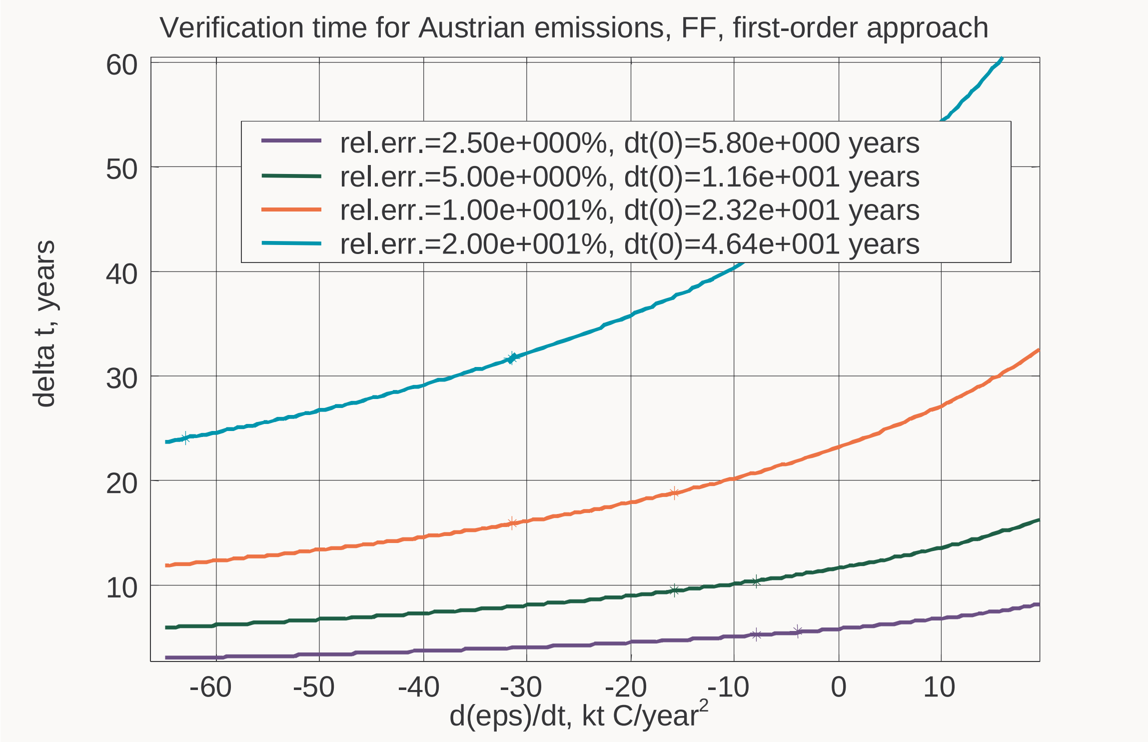


Figure 6: The VT associated with Austria's FF emissions [equation (3.10)] for $\varepsilon(t_0)$ ranging from 2.5% to 20% as a function of the rate of uncertainty change (d(eps)/dt). Abscissa is the rate of uncertainty change (d(eps)/dt) kt in C/year^2, ordinate is the VT in years. The relative uncertainties are recalculated to corresponding absolute values for 1993, which are required by equation (3.10); initial uncertainties (rel.err.) and the corresponding VT for the initial uncertainties (dt(0)) are presented.

3.3.2 Methodology for second-order approach in consideration of absolute uncertainty

As the next step, we developed a second-order approach for uncertainties in absolute terms, suggested by Jonas *et al.* (1999). We used two ways for developing this approach, namely direct (mentioned in this Section), and theoretically based (see Section 4). Thus, the VT calculations can be crosschecked, which allows us to eliminate errors.

At the beginning, we fit the emission data by a second power polynomial and the absolute uncertainty still follows a first-order polynomial. We calculate the first derivative in the central point (see Section 3.1), and this center is our starting point from which we estimate the VT (t_0). As in Jonas *et al.* (1999), we start from the assumption that the emissions change (signal) becomes verifiable after it outstrips the uncertainty:

$$\left| \left.\frac{dF}{dt}\right|_{t_0} (t - t_0) + \frac{1}{2} \left.\frac{d^2F}{dt^2}\right|_{t_0} (t - t_0)^2 \right| > \varepsilon(t_0) + \left.\frac{d\varepsilon}{dt}\right|_{t_0} (t - t_0) .$$

We regroup the coefficients and solve the equations for *t-t₀*.

$$t-t_0=\frac{-\left(\left.\frac{dF}{dt}\right|_{t_0}-\left.\frac{d\varepsilon}{dt}\right|_{t_0}\right)\pm\sqrt{\left(\left.\frac{dF}{dt}\right|_{t_0}-\left.\frac{d\varepsilon}{dt}\right|_{t_0}\right)^2+2*\left.\frac{d^2F}{dt^2}\right|_{t_0}*\varepsilon(t_0)}}{\left.\frac{d^2F}{dt^2}\right|_{t_0}}, \text{ if}$$

$$\left.\frac{dF}{dt}\right|_{t_0}*(t-t_0)+\frac{1}{2}\left.\frac{d^2F}{dt^2}\right|_{t_0}*(t-t_0)^2>0 \qquad (3.11)$$

and

$$t-t_0=\frac{-\left(\left.\frac{dF}{dt}\right|_{t_0}+\left.\frac{d\varepsilon}{dt}\right|_{t_0}\right)\pm\sqrt{\left(\left.\frac{dF}{dt}\right|_{t_0}+\left.\frac{d\varepsilon}{dt}\right|_{t_0}\right)^2-2*\left.\frac{d^2F}{dt^2}\right|_{t_0}*\varepsilon(t_0)}}{\left.\frac{d^2F}{dt^2}\right|_{t_0}}, \text{ if}$$

$$\left.\frac{dF}{dt}\right|_{t_0}*(t-t_0)+\frac{1}{2}\left.\frac{d^2F}{dt^2}\right|_{t_0}*(t-t_0)^2<0\,. \qquad (3.12)$$

After obtaining a set of solutions, we chose those that satisfy equation (3.11) or (3.12), are real (because of the physical meaning of time), greater than zero (because we 'look forward'), and are the smallest among the valid ones. Figures 7 and 8 depict Ukraine as an example. Its 1992–1996 FF emissions are fitted by a second-order polynomial, shown in Figure 7. The associated VT, in accordance with equations (3.11) and (3.12), is shown in Figure 8 for various initial assumptions of $\varepsilon(t_0)$ (t_0 = 1994).

If the solution (t-t_0) is inside the fitting interval (where we have data) the error of our estimate is defined by error fitting. Otherwise, we must consider the polynomial outside the fitting interval as extrapolation, and uncertainty in this case strongly depends on the number of data points used for fitting, the order of the polynomial used, and the distance from the fitting interval.

We also reveal some transition of the VT — rapid change of VT caused by a slight increase or decrease in the change of emissions over time (Figure 8). This effect is described in more detail in Section 4.

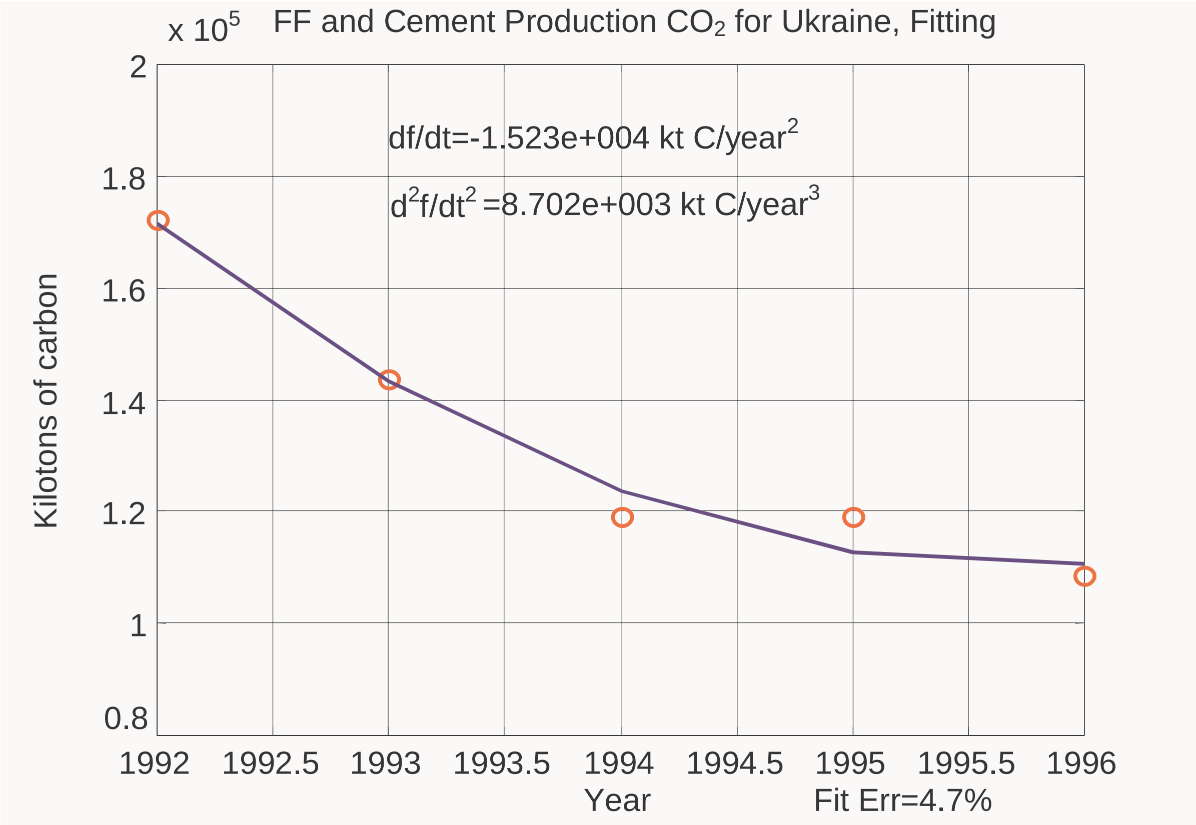


Figure 7: Ukraine's FF emissions for 1992–1996 and fitting by second-order polynomial. Fit Err is calculated as the square root of the sum of squares of the differences between data and regression relative to the emission level in 1992. df/dt and d^2f/dt^2 are the first and second derivatives of the polynomial in t = 1994, respectively.

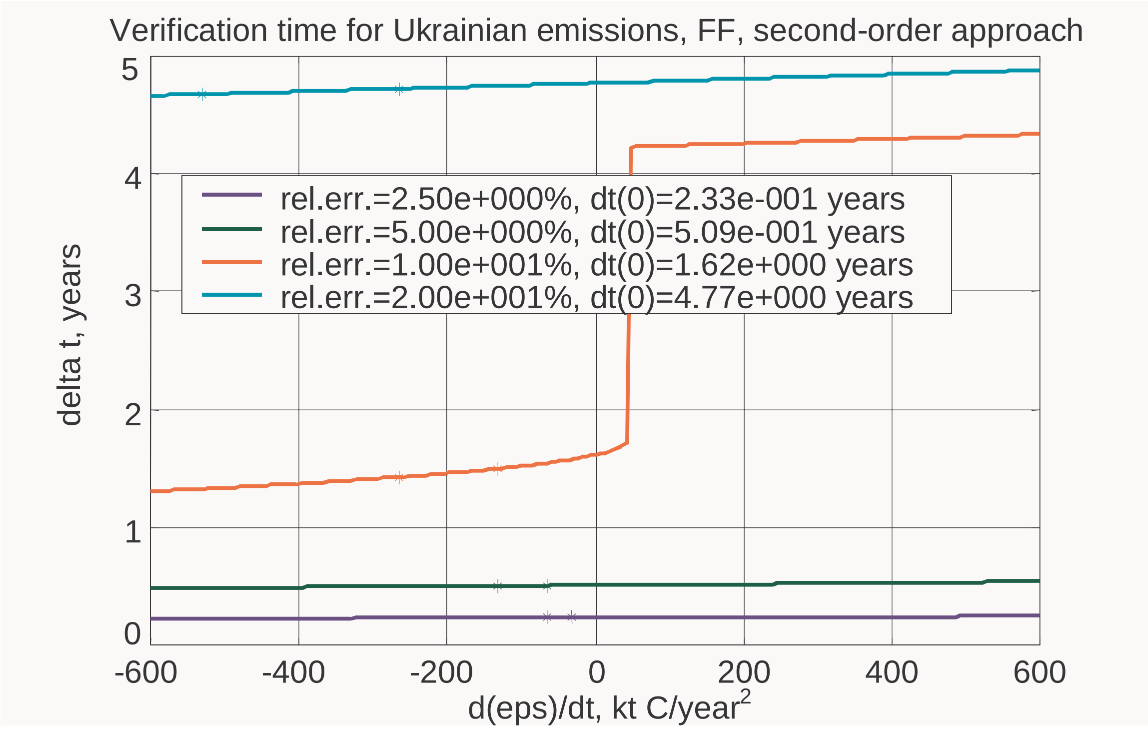


Figure 8: The VT associated with Ukraine's FF emissions [equations (3.11) and (3.12)] for $\varepsilon(t_0)$ ranging from 2.5% to 20% as a function of the rate of uncertainty change (d(eps)/dt). Abscissa is the rate of uncertainty change (d(eps)/dt) kt in C/year^2, ordinate is the VT in years. The relative uncertainties are recalculated to the corresponding absolute values for 1994, which are required by equations (3.11) and (3.12); initial uncertainties (rel.err.) and the corresponding VT for the initial uncertainties (dt(0)) are presented.

3.3.3 Methodology for VT calculations in consideration of relative uncertainty

Uncertainties are more typically presented in relative terms by the countries to the Kyoto Protocol. Therefore, it is natural to use uncertainty in relative terms for calculating the VT.

In this case we should find time *t*, which satisfies the inequity:

$$\left|F(t) - F(t_0)\right| > \varepsilon(t), \quad t > t_0, \tag{3.13}$$

as in previous cases, but uncertainty in absolute terms $\varepsilon(t)$ is calculated according to:

$$\varepsilon(t) = R(t)\, F(t).$$

Here, *F(t)* are emissions data (FF emissions data fitted with a polynomial), *R(t)* is the associated relative uncertainty, t_0 is the base year (e.g., 1990 for most Annex I countries), or a year relative to which we calculate the VT.

We fit the emissions data by a polynomial using the least squares technique and describe the relative uncertainty with a polynomial as well:

$$P(t) = P(t_0) + P'(t_0)\,(t - t_0) + \frac{P''(t_0)}{2}\,(t - t_0)^2 + \ldots + \frac{P^{(n)}(t_0)}{n!}\,(t - t_0)^n . \qquad (3.14)$$

Here, and in equations (3.15) to (3.17), the sign " $'$ " means " $\frac{d}{dt}$ ". Thus, we can rewrite inequity equation (3.13) using emissions and uncertainty in the form of equation (3.14):

$$\left| F'(t_0)\,(t - t_0) + \frac{F''(t_0)}{2}\,(t - t_0)^2 + \ldots + \frac{F^{(n)}(t_0)}{n!}\,(t - t_0)^n \right| > \ldots$$
$$\ldots > \left(R(t_0) + R'(t_0)\,(t - t_0) + \frac{R''(t_0)}{2}\,(t - t_0)^2 + \ldots + \frac{R^{(n)}(t_0)}{n!}\,(t - t_0)^n \right) \times \ldots \qquad (3.15)$$
$$\ldots \times \left(F(t_0) + F'(t_0)\,(t - t_0) + \frac{F''(t_0)}{2}\,(t - t_0)^2 + \ldots + \frac{F^{(n)}(t_0)}{n!}\,(t - t_0)^n \right).$$

Here, we use *F* for emissions and *R* for relative uncertainty. Now, we must solve equation (3.15) for $t\text{-}t_0$.

If the solution ($t\text{-}t_0$) is inside the fitting interval (where we have data) the error of our emissions estimate is defined by error fitting. Otherwise, we must consider the polynomial outside the fitting interval as extrapolation, and uncertainty in this case strongly depends on the number of data points used for fitting, the order of the polynomial used, and the distance from the fitting interval.

Let us consider the following cases:

(1) Emissions data are fitted with a first-order polynomial and relative uncertainty is constant *R=const*. Then, equation (3.15) reduces to:

$$\left| F'(t_0)\,(t - t_0) \right| > R(t_0)\,\left(F(t_0) + F'(t_0)\,(t - t_0) \right).$$

And the solution is determined with the expression:

$$t - t_0 = \begin{cases} \dfrac{R(t_0) * F(t_0)}{F'(t_0) * (1 - R(t_0))} & \text{if} \quad F'(t_0) > 0 \\ \infty & \text{if} \quad F'(t_0) = 0 \\ -\dfrac{R(t_0) * F(t_0)}{F'(t_0) * (1 + R(t_0))} & \text{if} \quad F'(t_0) < 0. \end{cases}$$

(2) If both emissions data and the associated relative uncertainty are modeled with first-order polynomials, equation (3.13) reduces to:

$$\left|F'(t_0)\,(t-t_0)\right| > \left(R(t_0)+R'(t_0)\,(t-t_0)\right)\left(F(t_0)+F'(t_0)\,(t-t_0)\right).$$

And the solution is determined with the expression:

$$t-t_0=\begin{cases} \dfrac{-\left(F'(t_0)(R(t_0)-1)+F(t_0)R'(t_0)\right)}{2F'(t_0)R'(t_0)} \\ \quad \pm\dfrac{\sqrt{\left(F'(t_0)*(R(t_0)-1)+F(t_0)*R'(t_0)\right)^2-4*F'(t_0)*R'(t_0)*F(t_0)*R(t_0)}}{2*F'(t_0)*R'(t_0)} & \text{if } F'(t_0)>0 \\ -\dfrac{R(t_0)}{R'(t_0)} & \text{if } F'(t_0)=0 \text{ and } R'(t_0)<0 \\ \text{NaN} & \text{if } F'(t_0)=0 \text{ and } R'(t_0)>0 \\ \dfrac{-\left(F'(t_0)*(R(t_0)+1)+F(t_0)*R'(t_0)\right)}{2*F'(t_0)*R'(t_0)} \\ \quad \pm\dfrac{\sqrt{\left(F'(t_0)*(R(t_0)+1)+F(t_0)*R'(t_0)\right)^2-4*F'(t_0)*R'(t_0)*F(t_0)*R(t_0)}}{2*F'(t_0)*R'(t_0)} & \text{if } F'(t_0)<0. \end{cases}$$

(3.16)

NaN = “Not a Number” and means that there is no solution.

Among these solutions we must select those that are real and greater than zero due to physical reasons, and we consider $t > t_0$, as well as we must select the smallest solution among the valid ones. Additionally, there are no solutions if uncertainty is increasing faster than emissions are changing.

(3) Emissions data are fitted by a second-order polynomial and the associated relative uncertainty by a first-order polynomial. Then we rewrite equation (3.13) as follows:

$$\left|F'(t_0)*(t-t_0)+\frac{1}{2}*F''*(t-t_0)^2\right| > \ldots$$
$$> \left(R(t_0)+R'(t_0)*(t-t_0)\right)*\left(F(t_0)+F'(t_0)*(t-t_0)+\frac{1}{2}*F''*(t-t_0)^2\right). \quad (3.17)$$

We used a numerical method to find the roots of the polynomial, equation (3.17), then among the roots we chose those that are real and greater than zero.

From a practical point of view, the third case is the most interesting among those considered above. Of course, it is possible and in some cases better to use fitting with higher-order polynomials, but in this work we only deal with the third case. Figures 9 and 10 depict Austria as an example. Its FF emissions are fitted by a second-order polynomial and are shown in Figure 9, while the associated VT, in accordance with equation (3.17), is shown in Figure 10 for various initial assumptions of $R(t_0)$ (t_0 = 1996). During the calculations R' is changing smoothly from –0.5%/year to +0.5%/year.

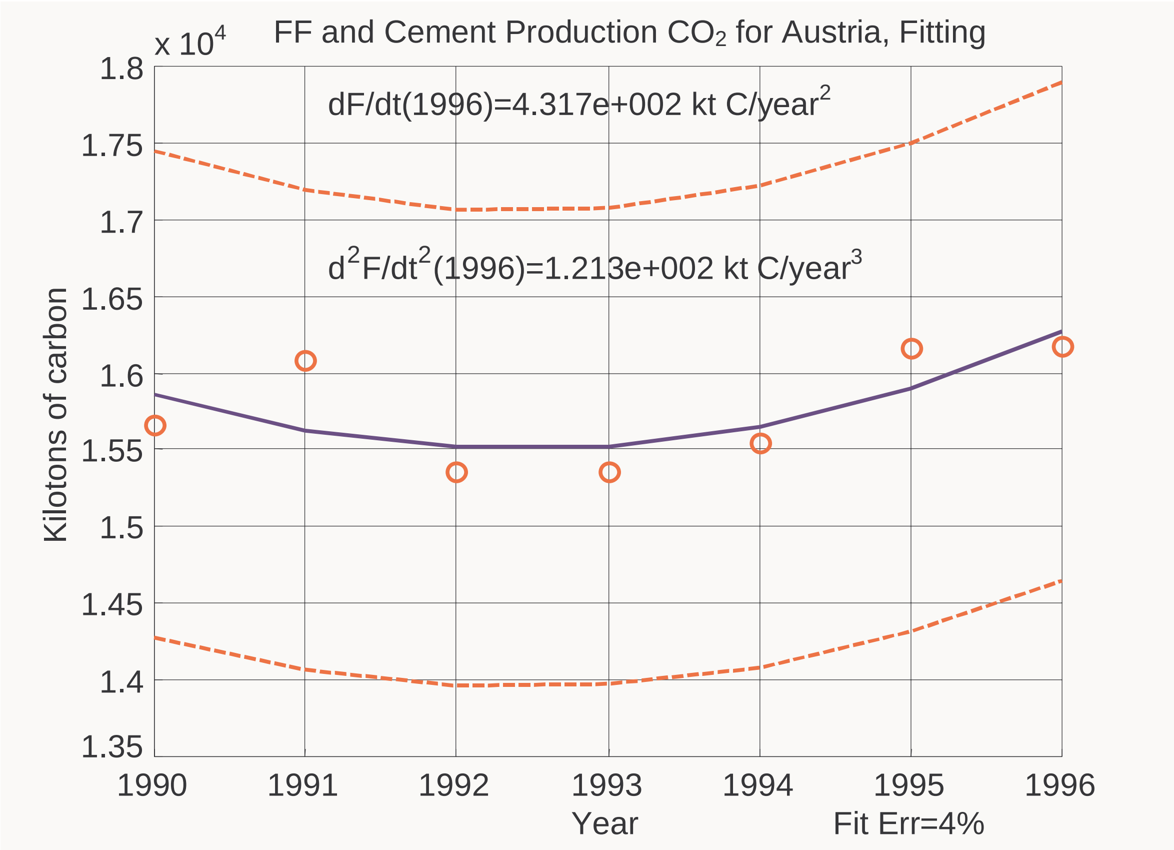


Figure 9: Austria's FF emissions for 1990–1996 and fitting by a second-order polynomial. The red lines are ±10% relative uncertainty boundaries around the polynomial, which is fitted by a first-order polynomial. Fit Err is calculated as the square root of the sum of squares of the differences between data and regression relative to the emission level in 1990. df/dt and d^2f/dt^2 are the first and second derivatives of the polynomial in t = 1996, respectively.

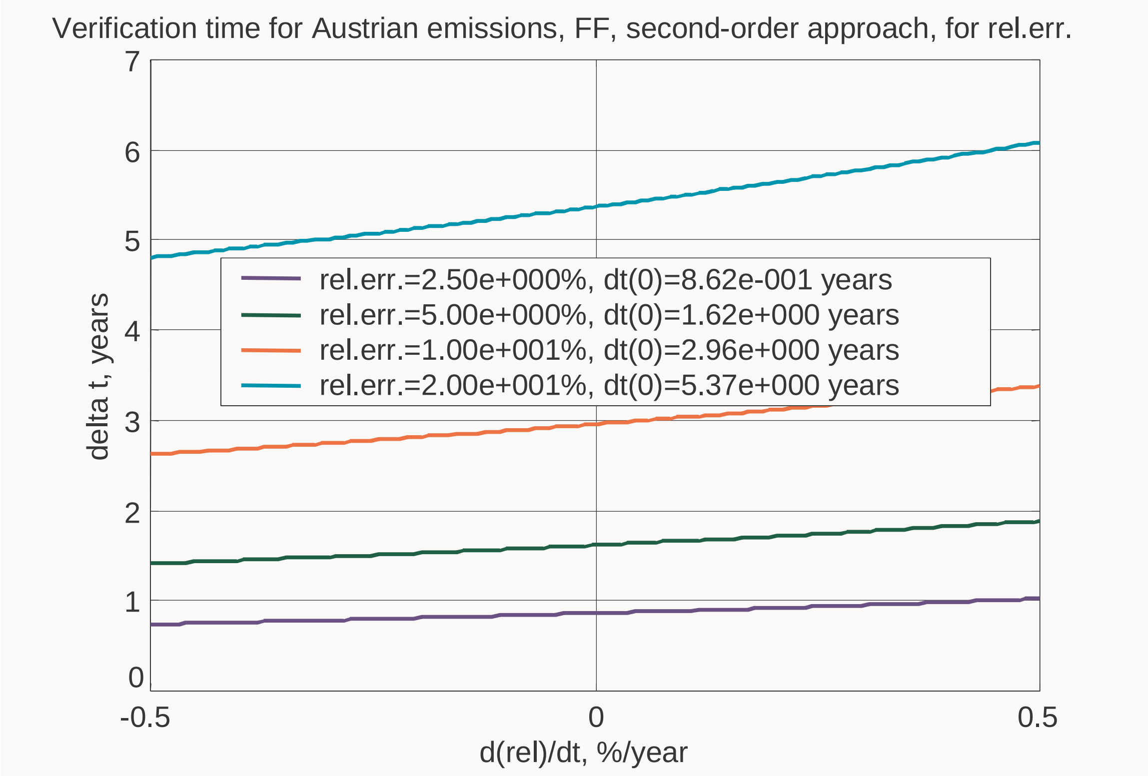


Figure 10: The VT associated with Austria's FF emission [equation (3.17)] for $R(t_0)$ ranging from 2.5% to 20% as a function of the rate of relative uncertainty change (d(rel)/dt). Abscissa is the rate of uncertainty change (d(rel)/dt) in %/year, ordinate is the VT in years. Initial uncertainties (rel.err.) and the corresponding VT for the initial uncertainties (dt(0)) are presented.

3.3.4 Results and discussion

The verification times of Annex I countries, calculated for absolute uncertainty (au), which corresponds to 10% relative uncertainty at the central point (1993 for most countries), and relative uncertainty (ru) of 10% are presented in Table 2 (calculations done by the methodology described in Sections 3.3.1 to 3.3.3).

For the calculations we used data from Marland *et al.*'s (1999a) database. We only took the last six available years: 1990–1996. The time after 1990 is taken into account in the Kyoto Protocol, but as the Protocol was adopted only in 1997, the emissions are not directly affected by it. This time interval presents a "business-as-usual case". It shows the verification conditions under which Annex I countries operated during 1990–1996.

Column 3 of Table 2 is calculated by equation (3.10), first-order approach; and column 4 by equation (3.11) or (3.12), second-order approach for uncertainty in absolute terms. The verification times are calculated starting from 1993 for most of the considered countries (i.e., t_0 = 1993).

Table 3.2. Verification times for Annex I countries (business-as-usual case).

Country	**Kyoto target, emissions reduction, %**	**VT (au, 1st), 1993[a] + … years** [Equ. (3.10)]	**VT (au, 2nd), 1993[a] + … years** [Equ. (3.11) and (3.12)]	**VT (ru, 2nd), 1990[a] + … years** [Equ. (3.17)]	**VT (ru, 2nd), 1996 + … years** [Equ. (3.17)]
Australia	+8	3.8	2.1	5.4	1.3
Austria	-8	23.2	4.6	8.4	3.0
Belgium	-8	11.0	4.6	7.8	3.35
Bulgaria	-8	3.5	8.65	2.2	4.8
Canada	-6	12.0	6.3	10.3	3.3
Croatia[a]	-5	4.6	2.5	4.4	1.8
Czech Republic[a]	-8	3.15	4.7	1.7	2.5
Denmark	-8	17.8	3.95	8.1	1.6
Estonia[a]	-8	1.4	3.9	0.7	1.55
European Community[b]	-8	-	-	-	-
Finland	-8	4.4	2.0	5.7	1.1
France	-8	12.4	5.5	10.1	3.1
Germany	-8	4.7	4.1	1.4	1.7
Greece	-8	4.4	3.4	5.0	3.0
Hungary	-6	4.6	4.3	1.5	1.8
Iceland	+10	7.4	2.5	6.4	1.4
Ireland	-8	3.5	3.0	4.1	2.75
Italy	-8	213.0	7.1	11.0	5.1
Japan	-6	7.7	4.7	7.15	3.8
Latvia[a]	-8	1.1	1.4	0.8	4.4
Liechtenstein[b]	-8	-	-	-	-
Lithuania[a]	-8	0.9	3.4	0.45	1.0
Luxembourg	-8	3.0	1.6	5.1	0.5
Monaco[b]	-8	-	-	-	-
Netherlands	-8	10.7	3.0	6.9	1.65
New Zealand	0	3.2	2.5	4.1	2.1
Norway	+1	1.9	2.7	1.1	6.1
Poland	-6	54.6	5.1	9.1	3.3
Portugal	-8	4.0	10.4	2.8	6.2
Romania	-8	2.5	3.9	10.2	3.4
Russian Federation[a]	0	2.0	5.6	1.2	3.0
Slovakia[a]	-8	4.3	2.2	0.8	0.85
Slovenia[a]	-8	1.55	1.0	3.0	0.6
Spain	-8	7.2	3.6	6.6	2.5
Sweden	-8	15.6	5.0	8.4	3.5
Switzerland	-8	49.9	4.35	8.7	2.4
Ukraine[a]	0	0.9	1.6	0.5	1.45
UK	-8	12.4	7.1	11.7	4.5
USA	-7	5.8	4.3	6.1	3.9

[a] For these countries data is only available since 1992, so the central point is 1994 not 1993, and the starting year is 1992 not 1990; we could not 'construct' the trajectories of reaching the Kyoto targets due to the lack of information.
[b] There is no data in the database for these parties.

Columns 5 and 6 in Table 2 are calculated by the methodology described in Section 3.3.3 (third case), second-order approach for uncertainty in relative terms. First, we calculated the VT starting from 1990 (i.e., t_0 = 1990; column 5), and then starting from 1996 (i.e., t_0 = 1996; column 6).

The VT calculated for a country, starting from the same year (1993), differs for the first- and second-order approaches (see columns 3 and 4 of Table 2). For some countries the difference is quite large (Austria, 23.2: 4.6 years; Denmark, 17.8: 3.95 years; Italy, 213.0: 7.1 years; Poland, 54.6: 5.1 years; and Switzerland, 49.9: 4.35 years). The difference is explained by the fact that the first and second order models of the emissions data differ a lot. The second-order method is more correct because the second-order polynomial fits the data better.

Verification times, calculated using the second-order method for relative uncertainty starting from 1990 and 1996, also differ. The difference is explained by the fact that the dynamics of emissions varies at different points of time.

3.4 Reaching the Kyoto Target: Construction of the Trajectory and VT Calculations

3.4.1 Methodology

We consider the FF system as a “black box” and only the output is known (Figure 11).

Figure 11: FF system as a “black box” model.

We assume that in future the system’s output has to comply with some agreed target in the future. We calculate the first and second derivatives (more exactly, the differences between neighboring points for a time unit, i.e., approximate derivatives) of the “output signal” in order to know the basic features of the system (“velocity” and “acceleration”). Then, we make a histogram of the absolute value of the derivatives in order to exclude possible errors and “smooth” the effect of uncertainty in the data as well as to make our conclusions more robust. For this purpose, we used a 90th percentile of the histograms (Figures 12 and 13, distribution of Austria’s FF emission derivatives; total number of first derivatives equals 177, and the second derivatives 176).

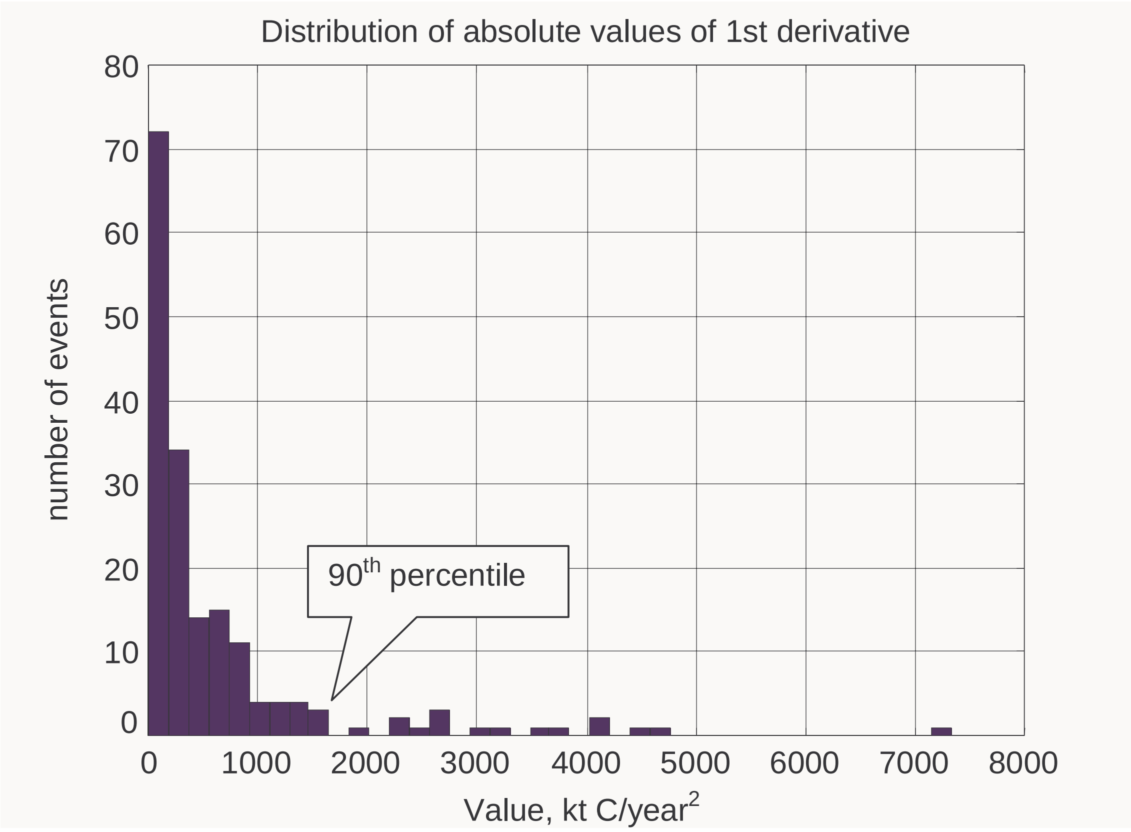


Figure 12: Histogram of the first derivative of Austria's FF CO_2 emissions (total number of the first derivatives equals 177).

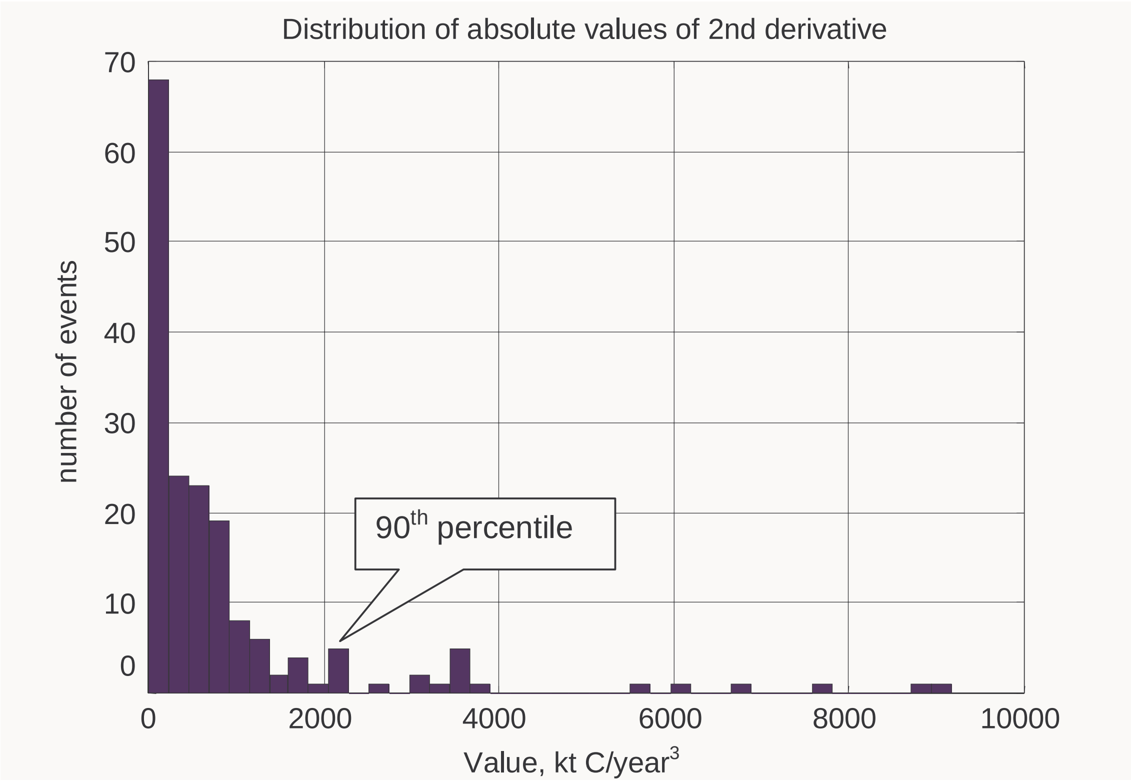


Figure 13: Histogram of the second derivative of Austria's FF CO_2 emissions (total number of the second derivatives equals 176).

We then "construct" the trajectory of CO_2 emissions between 1996 (last data point we have) and 2010 (middle of the Kyoto commitment period) in such a way that the Kyoto target is reached. We demand that the trajectory's first and second derivatives fall within the historical ranges, and that the emission changes are verifiable. We draw the trajectory by means of the least squares using data for 1990–1996 in general and the Kyoto target data, and calculate the VT beginning with 1996 by applying the method described in Section 3.3.3 (third case, equation 3.17). The trajectory and the VT, calculated for four different initial relative uncertainties, are illustrated in Figures 14 and 15 respectively, where Austria is an example.

We must also answer the question: How many last points of 1990–1996 should we take to 'construct' the trajectory? This can be answered as follows:

- to take as many points as possible, but
- the points must show a "strong trend", i.e., to lie on about one line,
- to take at least three last points in case the points change the overall trend significantly, and
- we can use relative error fitting (which is calculated as the square root of the sum of squares of the distances between data points and fitted points divided by base year data point) as a measure of "how good the fitting is", but there is no strong threshold.

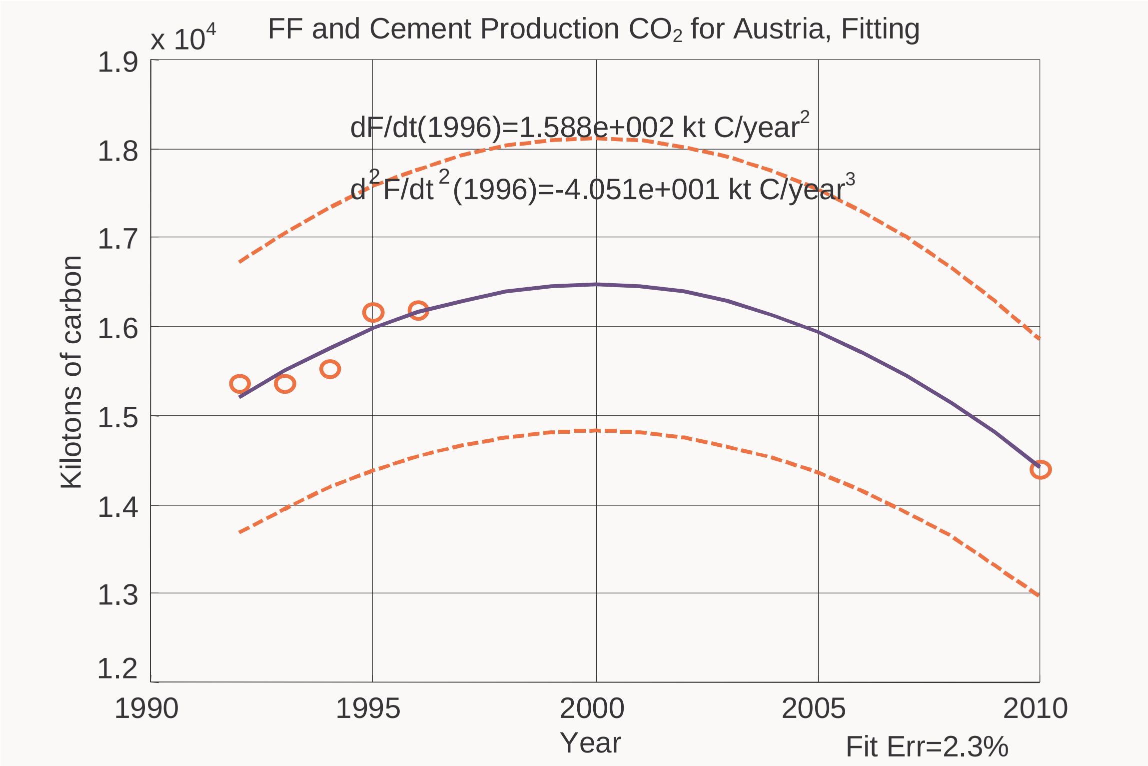


Figure 14: Trajectory of Austria reaching the Kyoto target that is constructed as described in Section 3.4.1. The red lines are ±10% relative uncertainty boundaries around the polynomial, which is fitted by a first order polynomial. Fit Err is calculated as the square root of the sum of squares of the differences between data and regression relative to the emission level in 1992. df/dt and d^2f/dt^2 are the first and second derivative of the polynomial in t = 1996, respectively.

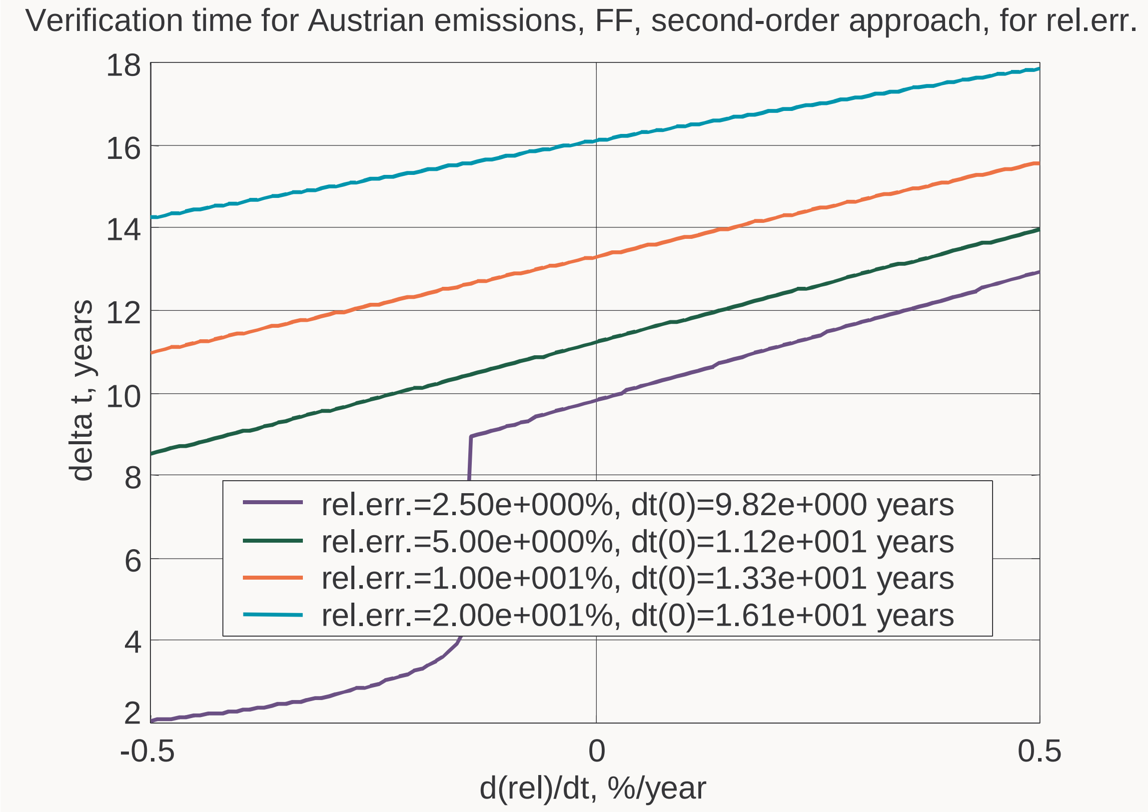


Figure 3.10: The VT associated with Austria's projected FF emissions [equation (3.17)], starting from 1996, for $R(t_0)$ ranging from 2.5% to 20% as a function of the rate of relative uncertainty change (d(rel)/dt). Abscissa is the rate of uncertainty change (d(rel)/dt) in %/year, ordinate is the VT in years. Initial uncertainties (rel.err.) and the corresponding VT for the initial uncertainties (dt(0)) are presented.

3.4.2 Results and discussion

For the calculations we used data from Marland *et al.*'s (1999a) database. According to Marland's (2000) suggestions, we assume that the uncertainty of emission estimates in relative terms is 10%. However, for countries that potentially cannot verify emission change within the Kyoto commitment period, we presented the VT for a smaller uncertainty (5% and 2.5%), or used dynamics of uncertainties.

The 90th percentiles of distribution of approximate first and second derivatives of the FF system, the maximal values of the first and second derivatives of theoretical trajectories, and the VT of the theoretical trajectories from 1996 for Annex I countries calculated for level uncertainty in relative terms (10%), are presented in Table 3 and the corresponding figures are in the Appendix.

Table 3: Parameters of the trajectory of reaching the Kyoto target for Annex I countries.

Country	Kyoto target, emissions reduction, %	90th perc. of 1st der., x10^3, kt C/yr^2	90th perc. of 2nd der., x10^3, kt C/yr^3	Max 1st der. of the trajectory x10^3, kt C/yr^2	Max 2nd der. of the trajectory x10^3, kt C/yr^3	VT (ru, 2nd) of trajectory, 1996[a] + … years
Group 1. Countries that cannot reach their Kyoto targets:						
Australia	+8	2.42	2.05	4.20	0.40	15.2/NR
Canada	-6	3.63	4.46	4.12	0.39	4.1/NR
Finland	-8	0.97	1.39	0.98	0.11	12.5/ NR
Netherlands	-8	2.14	3.20	3.25	0.40	2.5/NR
New Zealand	0	0.35	0.52	0.49	0.06	12.3/NR
Norway	+1	0.81	1.16	1.22	0.12	10.5/NR
Portugal	-8	0.43	0.71	0.56	0.05	10.7/NR
Spain	-8	2.18	2.62	3.62	0.40	12.4/NR
Group 2. Countries that cannot verify emission changes (for 10% initial uncertainty):						
Iceland	+10	0.06	0.12	0.02	0.001	22.4/NV
Romania	-8	0.01	0.02	0.001	0.0001	23.6/NV
UK	-8	6.92	9.75	1.56	0.09	33.7/NV
Group 3. Countries that can reach and verify their Kyoto Targets:						
Austria	-8	1.58	2.25	0.41	0.04	13.3
Belgium	-8	3.04	3.98	1.38	0.15	12.4
Bulgaria	-8	1.44	1.85	1.57	0.18	1.6/AR
France	-8	7.23	9.45	5.46	0.68	4.0
Germany	-8	15.20	18.34	7.67	0.73	14.0/AR
Greece	-8	1.04	1.24	0.93	0.09	11.9
Hungary	-6	1.00	1.25	0.71	0.08	14.8/AR
Ireland	-8	0.83	1.05	0.42	0.04	10.5
Italy	-8	4.42	5.19	2.64	0.27	13.8
Japan	-6	12.21	11.80	11.82	1.24	12.6
Luxembourg	-8	0.29	0.37	0.27	0.03	1.2/AR
Poland	-6	4.42	5.01	3.43	0.41	14.4
Sweden	-8	1.70	2.35	0.66	0.07	12.7
Switzerland	-8	0.78	1.08	0.30	0.03	14.6
USA	-7	51.71	71.50	40.81	3.76	12.0
Countries for which there is not enough data:						
Croatia[a]	-5	-	-	-	-	-
Czech Rep.[a]	-8	-	-	-	-	-
Denmark	-8	-	-	-	-	-
Estonia[a]	-8	-	-	-	-	-
European Com.[b]	-8	-	-	-	-	-
Latvia[a]	-8	-	-	-	-	-
Liechtenstein	-8	-	-	-	-	-
Lithuania[a]	-8	-	-	-	-	-
Monaco[b]	-8	-	-	-	-	-
Russian Fed.[a]	0	-	-	-	-	-
Slovakia[a]	-8	-	-	-	-	-
Slovenia[a]	-8	-	-	-	-	-
Ukraine[a]	0	-	-	-	-	-

NV = not verifiable; NR = not reachable; and AR = already reached.

[a] For these countries, data is available since 1992 but we could not ‘construct’ a trajectory of reaching the Kyoto targets due to lack of information.

[b] There is no data in the database for these parties.

In the first group of Table 3, there are the countries' physical properties of the FF systems that do not allow them to reach their Kyoto targets. This is described in the following paragraphs.

According to the Kyoto Protocol, Australia is allowed to increase its emissions by 8% in comparison to 1990. After 1992, Australia's CO_2 emissions from the FF system have a strong trend upward and in 1996 the emissions exceeded 108% of the 1990 level. If we 'construct' the trajectory of reaching the Kyoto target using this trend, Australia cannot reach its Kyoto target according to our model (note, that we only consider the FF system).

After 1994, the Netherlands' CO_2 emissions from the FF system has a strong trend upward and, according to our model, cannot reach its Kyoto target.

According to the Kyoto Protocol, New Zealand is allowed to freeze its net GHG emissions at the 1990 level. However, after 1990, there is a strong trend upward in CO_2 emissions from the FF system and, according to our model, New Zealand cannot reach its Kyoto target.

After 1990, Spain's CO_2 emissions from the FF system had a strong trend upward. According to our model, Spain cannot reach its Kyoto target.

In addition, in the first group there are also countries that have physical properties of the FF systems, which are quite close to those that allow them to reach their Kyoto targets. These countries are marked in gray and are described in the following paragraphs.

Canada is very close to reaching its Kyoto target, and if we use the 95^{th} percentile of the first derivative distribution (5.04×10^3 ktC/yr^2) instead of the 90^{th}, it could reach its Kyoto target according to our model.

Finland is also very close to reaching its Kyoto target, and if we use the 95^{th} percentile of the first derivative distribution (1.46×10^3 ktC/yr^2) instead of the 90^{th}, it could reach its Kyoto target according to our model.

According to the Kyoto Protocol, Norway is allowed to increase its emissions by 1% in comparison to 1990. After 1990, there is a strong trend upward in the FF system CO_2 emissions. Nevertheless, Norway is still potentially able to reach its Kyoto target, and if we use the 95^{th} percentile of the first derivative distribution (1.26×10^3 ktC/yr^2) instead of the 90^{th}, it could reach its Kyoto target according to our model.

The second group in Table 3 comprises of countries that cannot verify their FF emission changes within the Kyoto commitment period if the constant relative uncertainty of 10% is mentioned. These countries are described in the following paragraphs.

According to the Kyoto Protocol, Iceland is allowed to increase its emissions by 10% in comparison to 1990. In 1996, Iceland's CO_2 emissions from the FF system were less than 110% of the 1990 emissions from the FF system. This means that Iceland's FF emissions are within the Kyoto commitment. However, Iceland cannot verify the changes in its FF emissions by the end of the Kyoto commitment period if we assume a

10% relative uncertainty. Iceland could verify the emission change in about 9 years (starting from 1996) if the uncertainty could be reduced at 0.1% per year, starting from a 10% initial uncertainty, or about 3 years if we assume a 5% initial uncertainty (see the Appendix).

Romania could verify the change in its FF CO_2 emissions in about 14 years if we assume initial uncertainty to be 5% and would reduce at 0.3% per year, or in about 15 years if we assume initial uncertainty to be 10% and would reduce at 0.5% per year, starting from 1996 (see the Appendix).

The United Kingdom could verify the change in its FF CO_2 emissions in 4.3 years if we assume a 2.5% uncertainty, in about 10 years if the uncertainty in emission estimates would be reduced at 0.094% per year, and in about 12 years if the uncertainty in emission estimates would be reduced at 0.5% per year (see the Appendix).

The third group, comprising Austria, Belgium, France, Germany, Greece, Italy, Ireland, Japan, Norway, Poland, Sweden, Switzerland, and the USA are countries that are, in principle, potentially able, according to our model assumptions, to reach their Kyoto targets within the Kyoto commitment period and verify their changes in the emissions. Among the countries in this third group, there are those that have already reached their Kyoto targets.

In 1996, Bulgaria's CO_2 emissions from the FF system were less than 92% of the 1990 emissions from the FF system. This means that Bulgaria has already reached its Kyoto target but, according to our model, it cannot go upward so fast as to be exactly at the level of 92% of 1990.

In 1996, Germany's FF emissions were less than 92% of the 1990 emission level, which means that Germany has already reached its Kyoto target. Moreover, it can verify emission change if we assume a 10% initial uncertainty.

In 1996, Hungary's CO_2 emissions from the FF system were less than 94% of the 1990 emissions from the FF system. This means that Hungary has already reached its Kyoto target and, according to our model, it can go upward to be exactly at the level of 94% of 1990.

In 1996, Luxembourg's CO_2 emissions from the FF system were less than 92% of the 1990 emissions from the FF system. This means that Luxembourg has already reached its Kyoto target and, according to our model, it can go upward to be exactly at the level of 92% of 1990.

The weakness of the approach is due to the fact that there are not strong rules for constructing the trajectories for reaching the Kyoto target (more exactly, the rules are not well formalized). Thus, it is possible to make a few trajectories for each country, and obtain different results about a country's ability to reach its Kyoto target and verify the emission changes. But by indicating the countries that can be assigned to different groups if softer criteria are applied, we can make the calculations more reliable, and for the rest of the countries a slight change of the trajectory leaves them within the groups. We should also bear in mind that the study is illustrative because we consider only FF

CO_2 emissions and do not take into account the “additional activities” mentioned in the Kyoto Protocol (UNFCCC, 1997) that can alter the amount of emissions to be decreased due to FF systems.

A second approach to study the ability to reach and verify Kyoto commitments is developed in Section 4.

4 Smoothness of Emission Scenarios and Its Consequences for Verification Times

4.1 VT: Generalized Second-order Approach

In the previous section, it was discussed that the Kyoto obligations are not related to just emissions but rather to their change in relation to the so-called “base year”. In this section we express this change, called *signal*, by the difference:

$$\Delta f(t) \equiv f(t) - f(t_0) \ , \tag{4.1}$$

where $f(t)$ denotes the emissions at year t, and $f(t_0)$ the emissions at base year t_0. However, we want to emphasize that the discussed signal can be, in principle, associated to any dynamic “observable” that is changing in time. Hence, we can expect that the theory we have developed primarily for the net carbon emissions system can be applied to any of its sectors.

It is obvious that any measurable physical observable is not exactly known. While dealing with physical measurements one must also always take into account the corresponding *uncertainty*. Here, omitting fundamental questions about the possible nature of this uncertainty, we consider it as a smooth function $\varepsilon(t)$, which is bounded to the fundamental signal defined by equation (4.1).

The VT is a concept (Jonas *et al.*, 1999) that relies on the simple requirement of the relation between the signal and the corresponding uncertainty. It is defined as a solution of the relation:

$$\left|\Delta f(t_0 + \Delta t)\right| \geq \varepsilon(t_0 + \Delta t), \tag{4.2}$$

for Δt. This means that the VT, Δt, is a characteristic parameter of a given dynamic system, which corresponds to the time required by this system to outstrip its corresponding uncertainty.

4.2 Signal and Uncertainty Series Expansion

The actual solution of equation (4.2) depends on the form of the functions, which are supposed to describe the dynamics of the signal and uncertainty. A standard and most simple procedure made in such cases is to express both with the help of polynomial series obtained by Taylor’s n-th order expansion with respect to the parameter Δt:

$$f(t_0+\Delta t) \cong \sum_{k=0}^{n} s_k \cdot \Delta t^k \ ,$$
$$s_k = \frac{1}{k!}\frac{d^k}{dt^k} f(t_0) \ . \tag{4.3}$$

Here, we assume that all of the characteristic information on the system's dynamics is contained in the set of Taylor coefficients s_k.

We proceed similarly for the uncertainty function $\varepsilon(t)$:

$$\varepsilon(t_0+\Delta t) \cong \sum_{j=0}^{m} u_j \cdot \Delta t^j \ ,$$
$$u_j = \frac{1}{j!}\frac{d^j}{dt^j} \varepsilon(t_0) \ . \tag{4.4}$$

In this work, we will not consider higher than first-order uncertainty expansions.

An alternative way is to express the uncertainty by means of the so-called relative uncertainty function $r(t)$:

$$r(t) = \frac{\varepsilon(t)}{f(t)} \ . \tag{4.5}$$

The reason for introducing this notation arises because countries typically assign relative uncertainties to their national emissions. Thus:

$$\varepsilon(t_0+\Delta t) = r(t_0+\Delta t) \cdot f(t_0+\Delta t) \ . \tag{4.6}$$

In general, the relative uncertainty function $r(t)$ can also vary in time. However, in this work we treat it as constant. This means that the dynamics of uncertainty strictly follows the dynamics of the corresponding signal.

In the first step, one can also describe $\Delta f(t)$ by the first-order Taylor expansion. This was actually done in Jonas *et al.* (1999). The aim of this paper is to extend the approach presented in Jonas *et al.* (1999) to the second-order (and possibly higher) Taylor expansion for the signal and the first-order (and possibly higher) expansion for the uncertainty.

4.3 First-order Signal Versus First-order Uncertainty

As mentioned, this problem has already been solved (Jonas *et al.*, 1999). Here, we present an equivalent form of the solution. The underlying approach is also applied below.

Inserting equations (4.3) and (4.4) into (4.2) we obtain:

$$\left|s_1\,\Delta t\right| \geq r_0 \cdot s_0 + u_1\,\Delta t \;, \tag{4.7}$$

which defines the first-order VT problem. The initial uncertainty u_0 is expressed here in terms of the initial relative uncertainty r_0.

In dealing with equation (4.7), we consider the equality sign and investigate the properties of the normalized and dimensionless parameter $\Delta\tau$, which is equivalent to the VT Δt:

$$\Delta\tau \geq r_0 + \beta\,\Delta\tau \;. \tag{4.8}$$

This can be obtained with the following set of substitution:

$$\Delta t = t_c \cdot \Delta\tau \;,\; t_c = \frac{s_0}{|s_1|} \;,\; \beta = \frac{u_1}{|s_1|} \;. \tag{4.9}$$

We want to emphasize that the remaining parameter β is also dimensionless. As can be seen from equation (4.9), it can serve as an equivalent to u_1, the normalized rate of uncertainty change. The parameter t_c is a characteristic time constant, which takes into account the actual rate of the signal changes.

The solution for the smallest VT $\Delta\tau$ is immediate:

$$\Delta\tau \geq \frac{r_0}{1-\beta} \;. \tag{4.10}$$

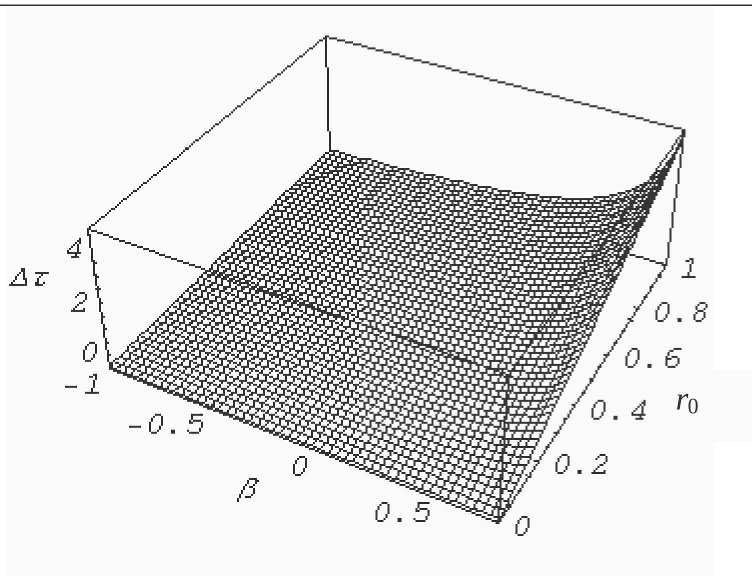
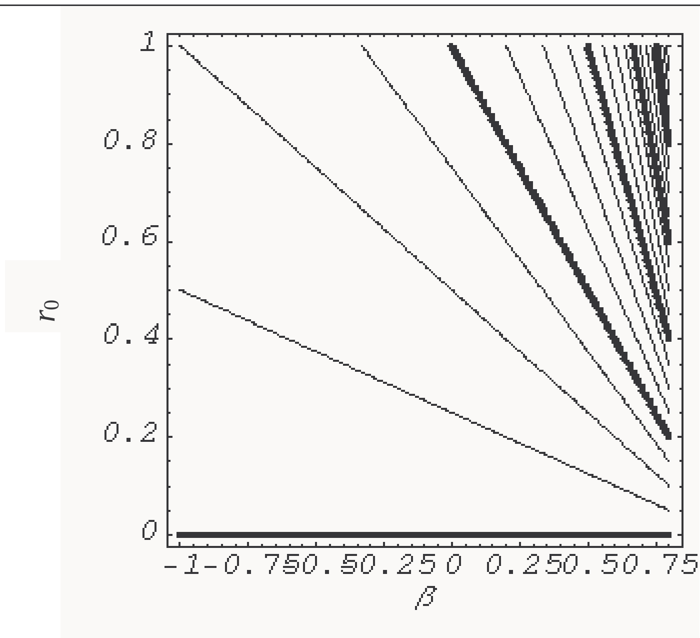
From this, one can see that the VT is proportional to the initial relative uncertainty r_0 and grows to infinity while the rate of uncertainty change ("u-velocity") approaches the rate of the signal change ("s-velocity"). This observation has already been made in Jonas *et al.* (1999).

We can see that the actual solution depends on only two parameters r_0 and β. Hence, all the properties of the system related to VT analysis can be investigated by means of the graphical representation of equation (4.10) and its corresponding map (top-down view), which we then call a VT diagram. Both are presented in the Table 4. VT isoclines are shown in steps of 0.25 in the VT diagram.

In certain situations we can treat Δt given. In this case, we can ask: Up to which value of relative error r_0 can we still assure verifiability of the signal? After reshaping (4.10) and remembering that $\Delta t = t_c \cdot \Delta\tau$, we obtain:

$$r_0 \leq \left(\frac{1}{sgn(s_1)} + \frac{t_c}{\Delta t} \right)^{-1} \;. \tag{4.11}$$

Table 4: First-order signal versus first-order uncertainty

VT EQUATION	$\lvert s_1\,\Delta t\rvert = u_0 + u_1\,\Delta t \;\;,\; u_0 \equiv r_0\, s_0$
NORMALIZATION	$\Delta\tau = \dfrac{\Delta t}{t_c}\;,\; t_c = \dfrac{s_0}{\lvert s_1\rvert}\;,\;\; \beta = \dfrac{u_1}{\lvert s_1\rvert}$
NORMALIZED VT EQUATION	$\Delta\,\tau = r_0 + \beta\,\Delta\,\tau$
SOLUTION	$\Delta\tau = \dfrac{r_0}{1-\beta}$
GRAPHICAL REPRESENTATION	
VT DIAGRAM	

4.4 Second-order Signal and First-order Absolute Uncertainty

In this case, equation (4.2) takes the form:

$$\left| s_2 \Delta t^2 + s_1 \Delta t \right| \geq u_0 + u_1 \Delta t \quad . \tag{4.12}$$

It is analyzed in a similar manner as in Section 4.3. The substitution:

$$\Delta \tau = \frac{\Delta t}{t_c} \ , \ t_c = \sqrt{\frac{u_0}{|s_2|}} \ \ , \ \alpha = \frac{s_1 \operatorname{sgn}(s_2)}{\sqrt{u_0 |s_2|}} \ , \ \beta = \frac{u_1}{\sqrt{u_0 |s_2|}} \quad , \tag{4.13}$$

leads to the inequality:

$$\left| \Delta \tau^2 + \alpha \Delta \tau \right| \geq 1 + \beta \Delta \tau \ \ , \tag{4.14}$$

which encounters not only the (normalized) rate of emission changes, α, but also the (normalized) rate of uncertainty changes, β. It can be shown that the solution for equation (4.14) (i.e., equation (4.14) in consideration of the equality sign) is given by:

$$\begin{gathered} \Delta \tau = \tfrac{1}{2}\left(\lambda \beta - \alpha + \lambda \sqrt{(\lambda \beta - \alpha)^2 + 4 \lambda} \right), \\ \lambda = \begin{cases} -1 & (\alpha, \beta) \in \Omega \\ \ \ 1 & (\alpha, \beta) \notin \Omega \end{cases} \\ \Omega = \left\{ (\alpha, \beta) : \alpha < 0 \wedge \ \beta + \alpha + 2 \leq 0 \wedge \ \left(\beta < \alpha \wedge \beta < \alpha^{-1} \vee \beta \geq \alpha \right) \right\}, \end{gathered} \tag{4.15}$$

is dependent on these rates only. We note that the rate of emissions changes, α, is usually given from the data; the rate of uncertainty changes, β, should be treated as a parameter. A graphical representation of equation (4.15) in the form of a map is presented in the Figure 16. We can observe there, the so-called bifurcation point leading to catastrophic behavior, which can be viewed as an analogue to a physical phenomenon known as phase-transition.

We want to emphasize that a “trick” used in the Sections 4.3 and 4.4 does not influence the quality of the solutions. The idea behind this method is to reduce the number of “free” parameters and to make them dimensionless. This can eventually enable us to make different signal-noise dynamics comparable. Actually, this feature is utilized in Section 4.7.

It is very intriguing, that this simple second-order scheme provides a non-trivial behavior. We can observe, for instance, that the bifurcation point, which is at point (-1,-1) may further lead to “jumpy” (discontinuous) behavior. The reason for this is illustrated in Figure 17. Table 5 summarizes the problem.

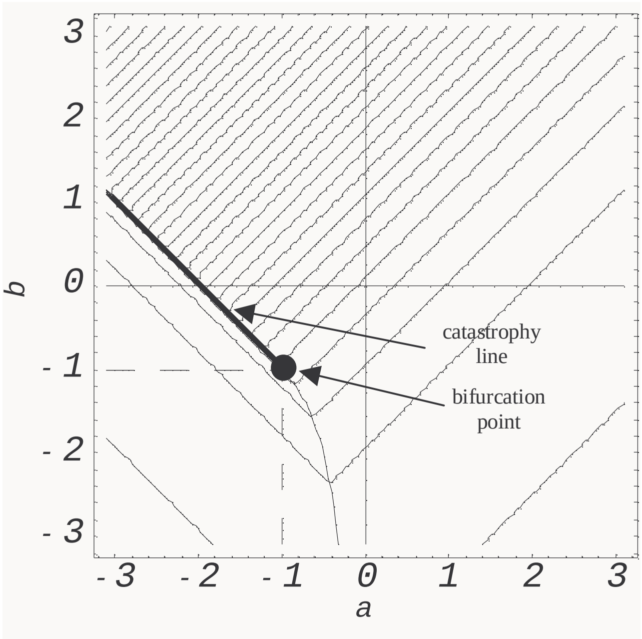


Figure 16: Illustration for the “jumpy” (discontinuous) behavior in VT diagrams.

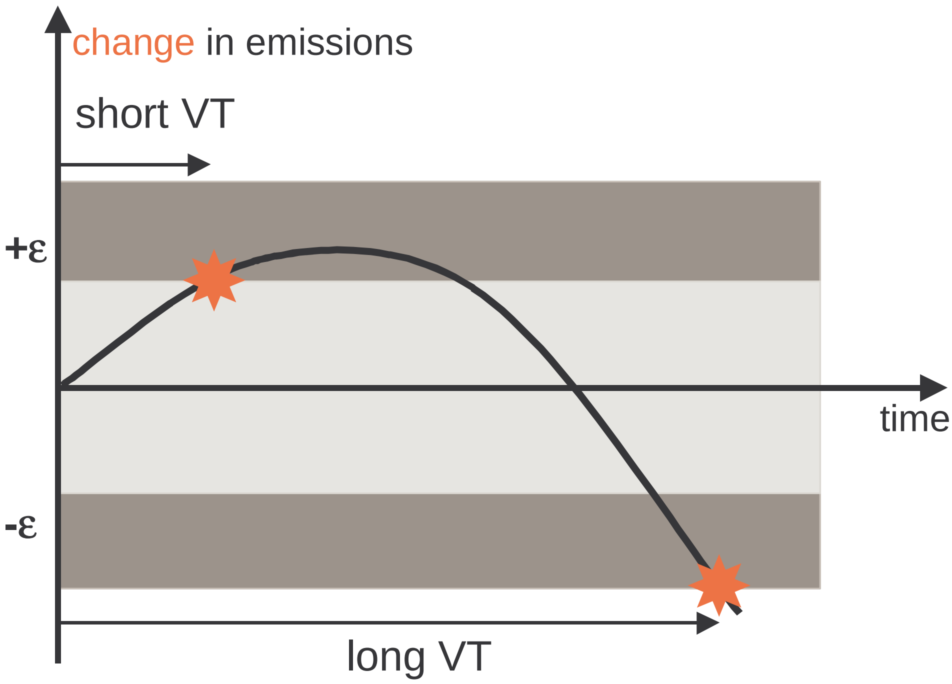
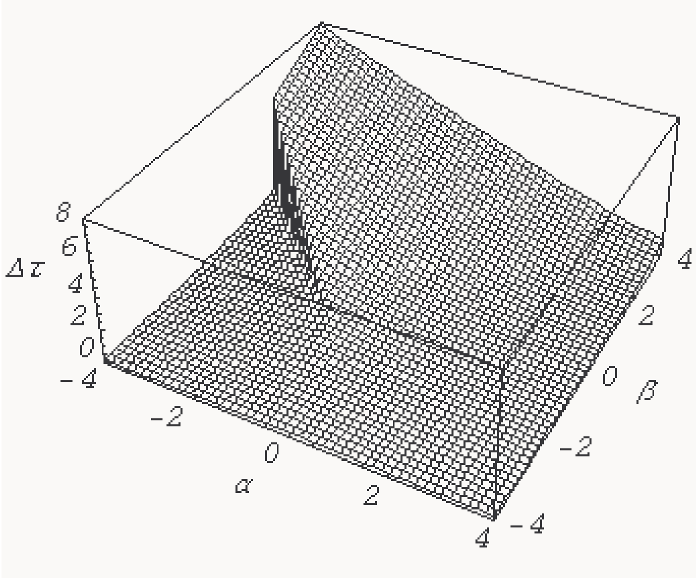
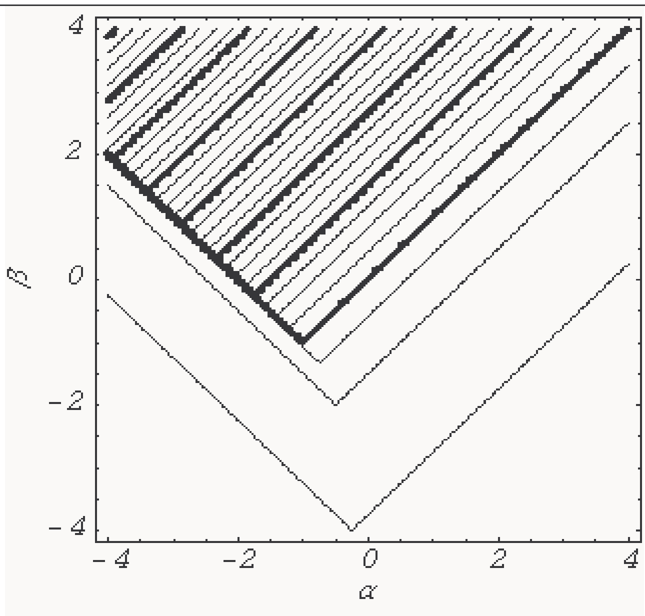


Figure 17: Illustration for the “jumpy” (discontinuous) behavior in VT diagrams.

Table 5: Second-order signal and first-order absolute uncertainty.

VT EQUATION	$\left\lvert s_2\,\Delta t^2 + s_1\,\Delta t \right\rvert = u_0 + u_1\,\Delta t$
NORMALIZATION	$\Delta\tau = \frac{\Delta t}{t_c}\ ,\ t_c = \sqrt{\frac{u_0}{\lvert s_2\rvert}}\ ,\ \alpha = \frac{s_1\,\mathrm{sgn}(s_2)}{\sqrt{u_0\,\lvert s_2\rvert}}\ ,\ \beta = \frac{u_1}{\sqrt{u_0\,\lvert s_2\rvert}}$
NORMALIZED VT EQUATION	$\left\lvert \Delta\tau^2 + \alpha\,\Delta\tau \right\rvert = 1 + \beta\,\Delta\tau$
SOLUTION	$\Delta\tau = \tfrac{1}{2}\left(\lambda\,\beta - \alpha + \lambda\sqrt{(\lambda\,\beta - \alpha)^2 + 4\,\lambda}\right),$ $\lambda = \begin{cases} -1 & (\alpha,\beta)\in\Omega \\ 1 & (\alpha,\beta)\notin\Omega \end{cases}$ $\Omega = \left\{(\alpha,\beta) : \alpha < 0 \wedge \beta + \alpha + 2 \le 0 \wedge \left(\beta < \alpha \wedge \beta < \alpha^{-1} \vee \beta \ge \alpha\right)\right\}$
GRAPHICAL REPRESENTATION	
VT DIAGRAM	

4.5 Second-order Signal and Constant Absolute Uncertainty

The way of normalizing equation (4.7) can also be extended to this case. For the case of a constant absolute uncertainty in equation (4.2) we have:

$$\left| s_1\,\Delta t + s_2\,\Delta t^2 \right| \geq r_0\, s_0 \quad . \tag{4.16}$$

By applying the substitution:

$$\Delta\tau = \frac{\Delta t}{t_c}\ ,\ t_c = \sqrt{\frac{s_0}{|s_2|}}\ ,\ \alpha = \frac{s_1\,\mathrm{sgn}(s_2)}{\sqrt{s_0\,|s_2|}} \quad , \tag{4.17}$$

we transform equation (4.16) into:

$$\left| \Delta\tau^2 + \alpha\,\Delta\tau \right| \geq r_0 \quad . \tag{4.18}$$

Once again, we can see that equation (4.18) is determined by only two parameters instead of four, as it was in (4.16). Now, parameter α can be understood as a (dimensionless) normalized rate of emission changes, while r_0 retains its meaning of the initial relative uncertainty.

It can be shown that inequality equation (4.18) is solved by:

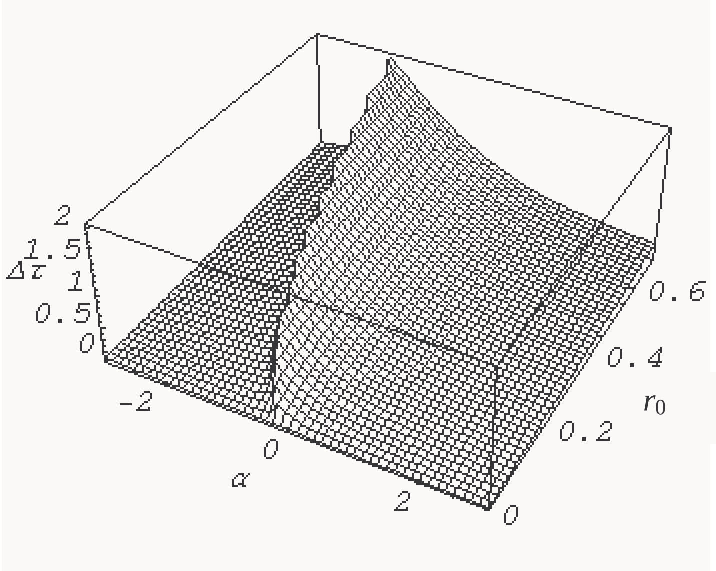
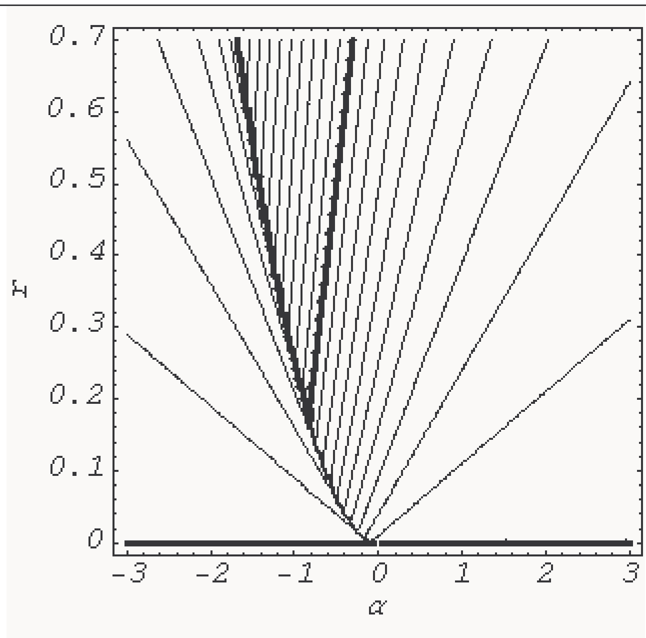
$$\Delta\tau = \tfrac{1}{2}\left(-\alpha + \lambda\sqrt{\alpha^2 + 4\lambda r} \right) , \tag{4.19}$$

where:

$$\lambda = \begin{cases} 1 & \text{for } \alpha > -2\sqrt{r}\ , \\ -1 & \text{for } \alpha \leq -2\sqrt{r}\ . \end{cases} \tag{4.20}$$

We can see that the VT actually depends on the normalized rate of emission change α, (which, in turn, depends on the sign of the “signal acceleration” s_2) and the actual value of initial relative uncertainty r_0. In the graphs in Table 6, we present the behavior of (normalized) VT $\Delta\tau$. VT isoclines in the associated VT diagram in Table 6 are shown in steps of 0.10.

Table 6: Second-order signal and constant absolute uncertainty.

VT EQUATION	$\left\| s_1\,\Delta t + s_2\,\Delta t^2 \right\| = r_0\, s_0$
NORMALIZATION	$\Delta\tau = \dfrac{\Delta t}{t_c}$, $t_c = \sqrt{\dfrac{s_0}{\|s_2\|}}$, $\alpha = \dfrac{s_1\,\mathrm{sgn}(s_2)}{\sqrt{s_0\,\|s_2\|}}$
NORMALIZED VT EQUATION	$\left\| \Delta\tau^2 + \alpha\,\Delta\tau \right\| = r_0$
SOLUTION	$\Delta\tau = \frac{1}{2}\left(-\alpha + \lambda\sqrt{\alpha^2 + 4\lambda\, r_0}\right)$, $\lambda = \begin{cases} 1 & \text{for } \alpha > -2\sqrt{r_0} \ , \\ -1 & \text{for } \alpha \le -2\sqrt{r_0} \ . \end{cases}$
GRAPHICAL REPRESENTATION	
VT DIAGRAM	

4.6 Second-order Signal and Constant Relative Uncertainty

In the case when the relative uncertainty is considered as constant, equation (4.2) takes the form $\left|s_1\Delta t + s_2\Delta t^2\right| \ge r\left|s_0 + s_1\Delta t + s_2\Delta t^2\right|$. We can apply the same set of substitutions equation (4.17) and generally the meaning of the relative uncertainty *r*:

$$\rho = r\,\mathrm{sgn}(s_2)\ . \tag{4.21}$$

With equations (4.17) and (4.21) we obtain:

$$\left|\Delta\tau^2 + \alpha\Delta t\right| \ge \left|\rho\right| + \rho\Delta\tau(\Delta\tau + \alpha) \tag{4.22}$$

and

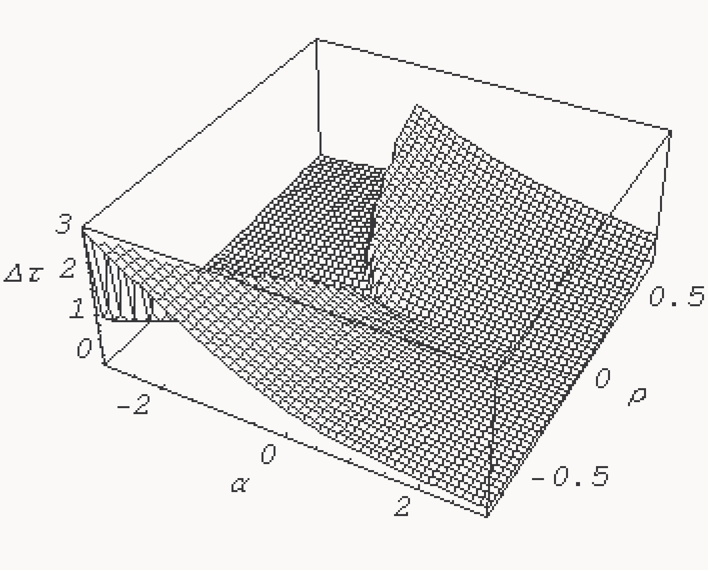
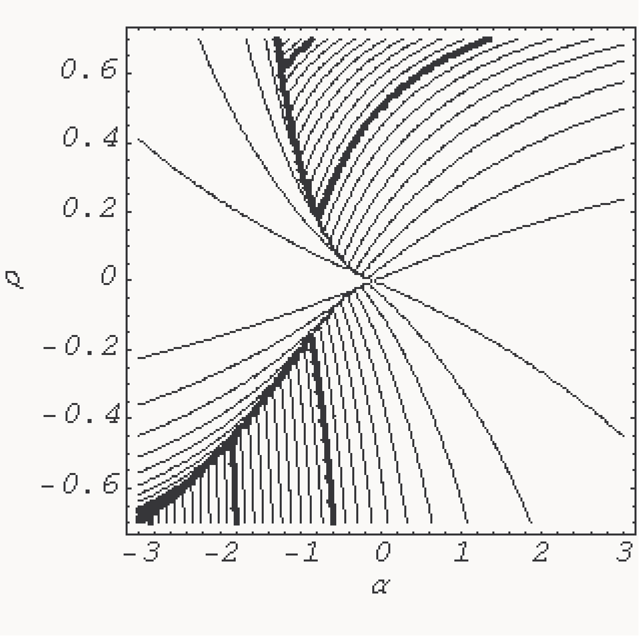
$$\Delta\tau = \tfrac{1}{2}\left(-\alpha + \lambda\sqrt{\alpha^2 + 4\left|\rho\right|/(\lambda - \rho)}\right) \tag{4.23}$$

as the solution of the normalized equation (i.e., equation (4.22) in consideration of the equality sign), where:

$$\lambda = \begin{cases} 1 & \alpha > -2\sqrt{\left|\rho\right|/(1+\rho)}\ , \\ -1 & \alpha \le -2\sqrt{\left|\rho\right|/(1+\rho)}\ . \end{cases} \tag{4.24}$$

In general, the VT diagram (see Table 7) related to this case is qualitatively similar to that obtained in Section 4.5. However, the VT $\Delta\tau$ for the case when the "velocity" s_1 of the signal increases (positive "acceleration") is different when it decreases (negative "acceleration"), and the difference becomes stronger for the big values of the relative uncertainty *r* as well as for the extreme values of the normalized rate of signal changes α.

Table 7: Second-order signal and constant relative uncertainty.

VT EQUATION	$\left\| s_1 \, \Delta t + s_2 \, \Delta t^2 \right\| = r \left(s_0 + s_1 \, \Delta t + s_2 \, \Delta t^2 \right)$
NORMALIZATION	$\Delta \tau = \frac{\Delta t}{t_c} \, , \, t_c = \sqrt{\frac{s_0}{\|s_2\|}} \; , \; \alpha = \frac{s_1 \, \mathrm{sgn}(s_2)}{\sqrt{s_0 \|s_2\|}} \; , \; \rho = r \, \mathrm{sgn}(s_2)$
NORMALIZED VT EQUATION	$\left\| \Delta \tau^2 + \alpha \Delta \tau \right\| = \|\rho\| + \rho \Delta \tau (\Delta \tau + \alpha)$
SOLUTION	$\Delta \tau = \frac{1}{2}\left(-\alpha + \lambda \sqrt{\alpha^2 + 4\|\rho\| / (\lambda - \rho)} \right)$ $\lambda = \begin{cases} 1 & \alpha > -2\sqrt{\|\rho\| / (1+\rho)} \\ -1 & \alpha \le -2\sqrt{\|\rho\| / (1+\rho)} \end{cases}$
GRAPHICAL REPRESENTATION	
VT DIAGRAM	

4.7 Matching Past with Future: Consequences of the Signal Function Smoothness

After the ratification of the Kyoto Protocol, countries to the Protocol are obliged to reduce (or limit) their annual net emissions to a certain value, specific to the country, called the commitment level. In general, this level is related to the annual net emissions in 1990 (base year). The commitment level is defined as a certain percentage of these emissions. This enables us to not deal with emission data as reported in the normal way, but with normalized data relative to base year emissions. In this way, each country starts at its base year from the dimensionless emission unit one. In these terms, the specific country obligation can be described as (1-δ), where parameter δ is the committed fractional emission reduction (limitation) in absolute terms.

Below, we discuss the consequences of the smoothness requirement on a signal function for modeling the transition period. Here, we understand smoothness as preserving continuity up to a desired order of derivative. In the case when a signal is modeled by a polynomial of the *n*-th degree, all the derivatives up to order (*n*-1) are continuous. Figure 18 presents the continuity idea for the signal and its first derivative ("velocity").

By taking $t = 2000$ as the "current" year, $t = 1990$ as the "base" year, and $t = 2010$ as commitment year, we can rescale the time axis taking the base year $t_B = -1$, current year $t_C = 0$, and the Kyoto commitment year $\mathrm{t_C} = 1$. If, by $f(t)$, we denote the signal function that approximates the already known historical data, and by dashed $\tilde{f}(t)$ we denote the "forced future" scenario, taking into account the continuity requirement, we can write:

$$
\begin{gathered}
f(-1) = 1 \,, \\
\tilde{f}(1) = 1 - \delta \,, \\
f^{(i)}(0) = \tilde{f}^{(i)}(0) \,, \\
i = 0, \ldots, n-1
\end{gathered}
\tag{4.25}
$$

where *n* is the order of the polynomials describing the emissions prior to and after 2000.

For analyzing the second-order VT problem, we use the second-order approach. This is equivalent to approximating the signal function, for a given time interval, with a parabola. Below, we deal with the parabolic models of the (post base year) history and the Kyoto scenario.

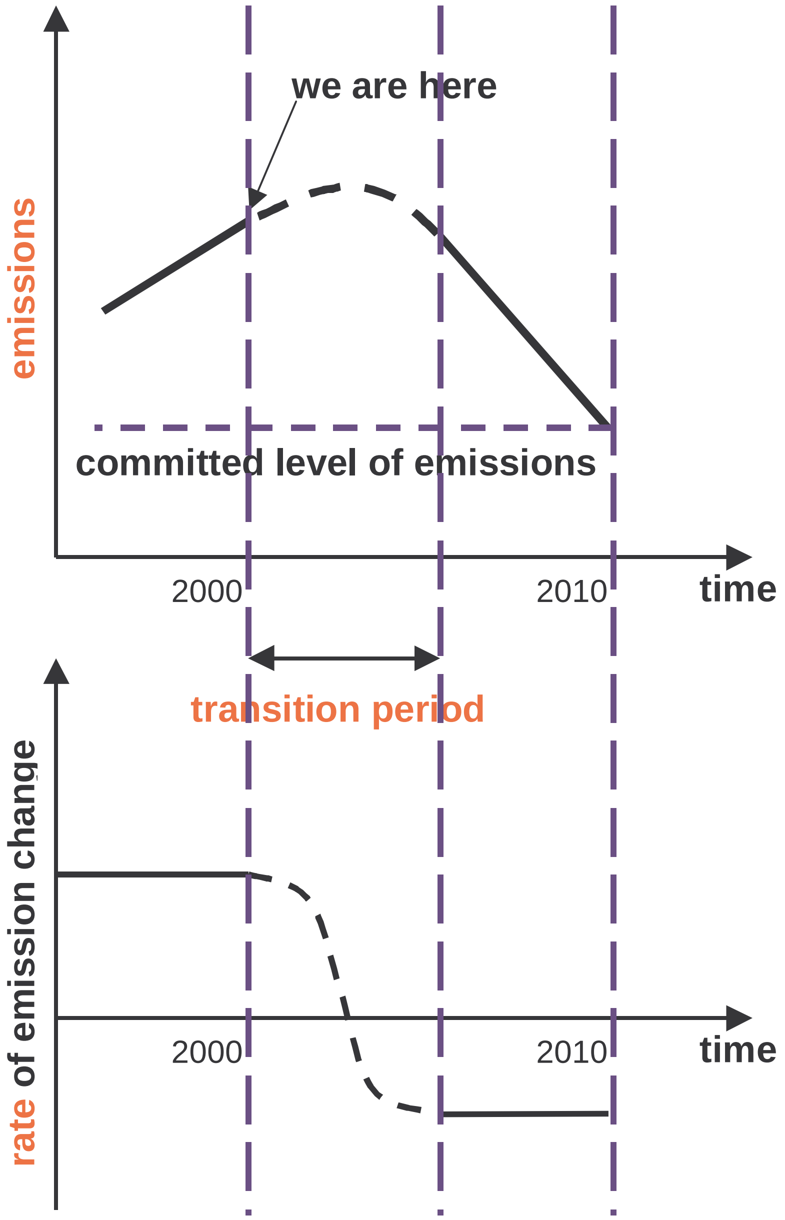


Figure 18: The idea of a smooth transition in reaching a “forced future” (emissions in commitment year).

Taking into account the second-order Taylor expansion of the signals:

$$f(t) = s_0 + s_1 t + s_2 t^2 \tag{4.26}$$

and

$$\tilde{f}(t) = \tilde{s}_0 + \tilde{s}_1 t + \tilde{s}_2 t^2 , \tag{4.27}$$

respectively, and equation (4.25) we have:

$$\begin{gathered} s_0 - s_1 + s_2 = 1 , \\ \tilde{s}_0 + \tilde{s}_1 + \tilde{s}_2 = 1 - \delta , \\ s_0 = \tilde{s}_0 , \\ s_1 = \tilde{s}_1 . \end{gathered} \tag{4.28}$$

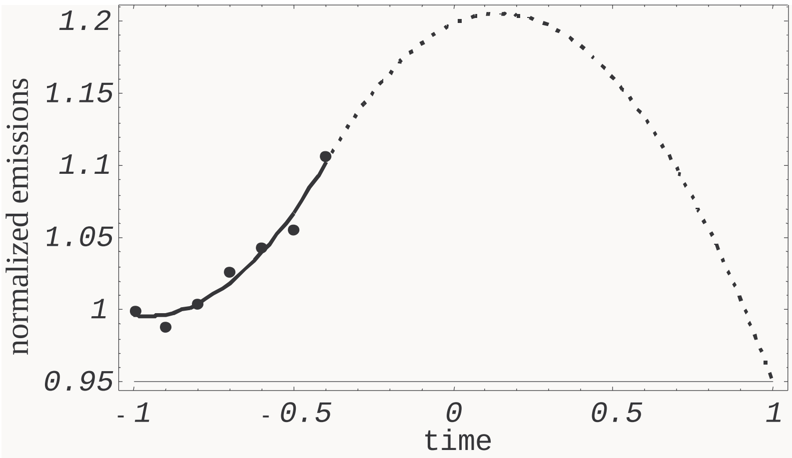
According to equation (4.28) only two independent parameters remain, namely s_0 (the value of the signal in 2000) and s_1 (which can be understood as "velocity" of the signal in 2000). If we rewrite s_0 in the form $s_0 = 1 + \Delta$, which anticipates that the current signal is different than the signal in the base year, we obtain the equation for the second-order polynomial that exactly reaches the Kyoto target ("forced future") and fulfills the requirement of continuing smoothly with the past signal:

$$\tilde{f}(t) = (1 + \Delta) + s_1 t - (\delta + \Delta + s_1) t^2 . \tag{4.29}$$

In Table 8a–f, we show examples of the construction presented for several Annex I countries. A 5% reduction limit ($\delta = 0.05$) and base year $t = 1990$ was assumed, as they stand as an obligation for most Annex I countries.

Tables 9 and 10 present the analytical formulas and corresponding numerical values of the normalized rates of emission changes (α and $\tilde{\alpha}$) and the characteristic times (t_c and $\tilde{t}_c$) for a set of several Annex I countries with different kinds of past and future dynamics. The values in Table 10 can be then directly applied to determine the VT by using VT diagrams from Tables 6 and 7. The advantage of this approach relies on the direct possibility to observe how the variation of the constant absolute uncertainty r and the constant relative uncertainty ρ influence the value of the VT. It is especially important in cases when the value of the parameter α (or $\tilde{\alpha}$) is negative and, according to the graphs in Tables 6 and 7, may lead to dramatic changes of VT. In these situations, an analyzed country may substantially benefit (by means of VT decrease) because of the uncertainty reduction. On the other hand, an increase of the uncertainty may lead to a dramatic increase of the VT. For instance, the VT for Japan in the case of a 14% uncertainty is four times greater than in the case of a 14% uncertainty.

Table 8a,b,c: “Matching past with future” graphs for several Annex I countries.



USA

$s_0 = 1.31$

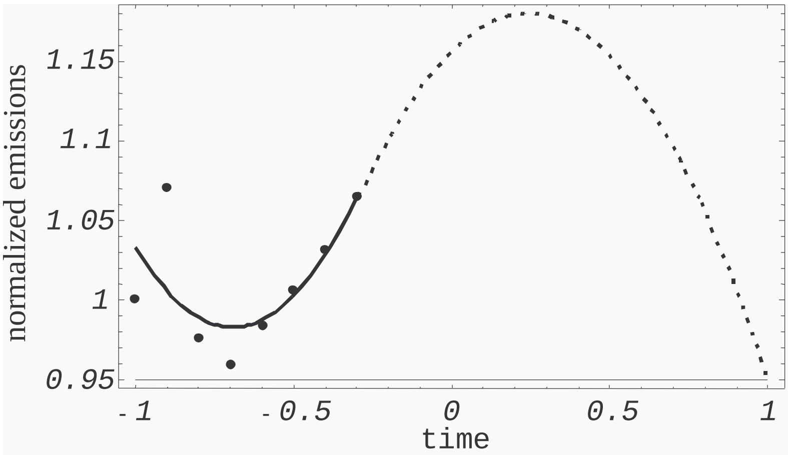
$s_1 = 0.65$

$s_2 = 0.34$

$\bar{s}_0 = 1.2$

$\bar{s}_1 = 0.1$

$\bar{s}_2 = -0.35$



Austria

$s_0 = 1.24$

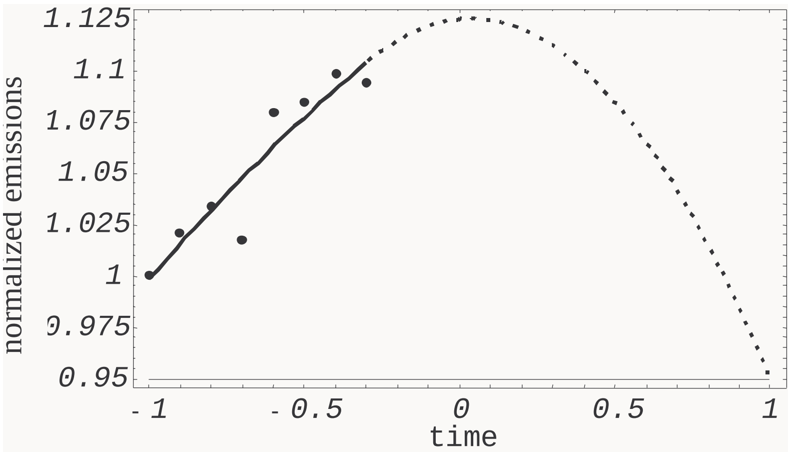
$s_1 = 0.73$

$s_2 = 0.53$

$\bar{s}_0 = 1.16$

$\bar{s}_1 = 0.2$

$\bar{s}_2 = -0.4$



Japan

$s_0 = 1.14$

$s_1 = 0.11$

$s_2 = -0.03$

$\bar{s}_0 = 1.13$

$\bar{s}_1 = 0.01$

$\bar{s}_2 = -0.19$

Table 8d,e,f: “Matching past with future” graphs for several Annex I countries.

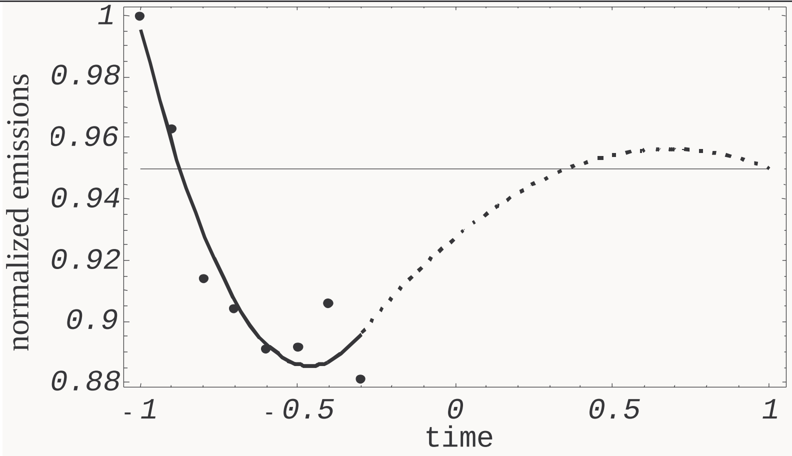
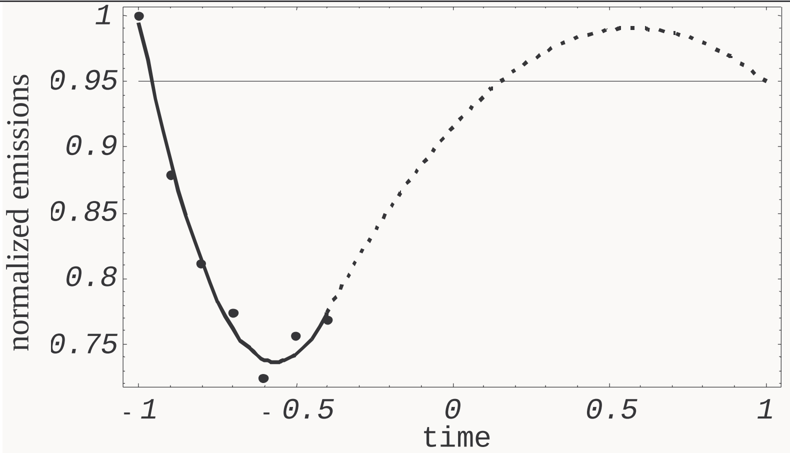
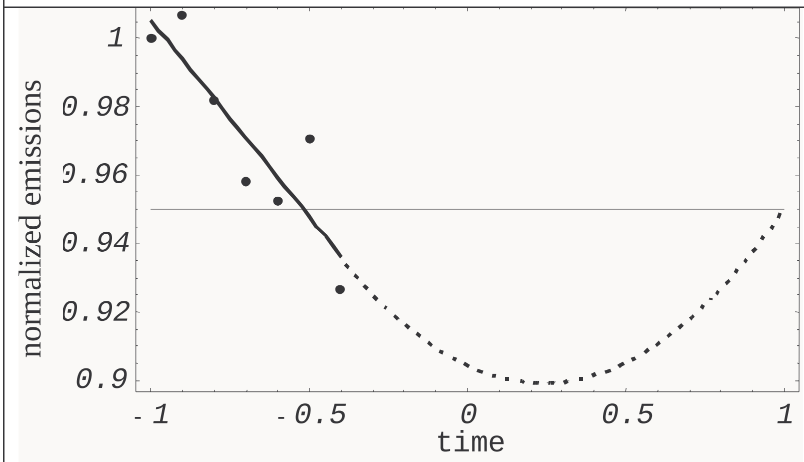
	**Germany** $s_0 = 0.97$ $s_1 = 0.36$ $s_2 = 0.38$ $\bar{s}_0 = 0.93$ $\bar{s}_1 = 0.09$ $\bar{s}_2 = -0.06$
	**Slovakia** $s_0 = 1.17$ $s_1 = 1.53$ $s_2 = 1.36$ $\bar{s}_0 = 0.92$ $\bar{s}_1 = 0.26$ $\bar{s}_2 = -0.23$
	**UK** $s_0 = 0.89$ $s_1 = -0.12$ $s_2 = 0.$ $s_0 = 0.9$ $s_1 = -0.04$ $s_2 = 0.09$

Table 9: Applying the case "second-order signal and constant relative uncertainty" (see Section 4.5).

"Past"	"Forced Future"
$t_c = \sqrt{\dfrac{s_0}{\lvert s_2 \rvert}} = \sqrt{\dfrac{1+\Delta}{\lvert s_1 - \Delta \rvert}}$	$\tilde{t}_c = \sqrt{\dfrac{s_0}{\lvert \tilde{s}_2 \rvert}} = \sqrt{\dfrac{1+\Delta}{\lvert \delta + s_1 + \Delta \rvert}}$
$\alpha = \begin{cases} \dfrac{s_1}{\sqrt{(1+\Delta)\,\lvert s_1 - \Delta \rvert}} & s_1 - \Delta \geq 0 \\ \dfrac{-s_1}{\sqrt{(1+\Delta)\,\lvert s_1 - \Delta \rvert}} & s_1 - \Delta < 0 \end{cases}$	$\tilde{\alpha} = \begin{cases} \dfrac{s_1}{\sqrt{(1+\Delta)\,\lvert \delta + s_1 + \Delta \rvert}} & s + s_1 + \Delta \geq 0 \\ \dfrac{-s_1}{\sqrt{(1+\Delta)\,\lvert \delta + s_1 + \Delta \rvert}} & s + s_1 + \Delta < 0 \end{cases}$

Table 10: Numerical values for the characteristic times (t_c) and the normalized rate of emission changes (α) (according to Table 9).

Country	"Past"		"Forced Future"	
	t_c	α	$\tilde{t}_c$	$\tilde{\alpha}$
USA	2.0	1.0	1.9	-0.2
Germany	1.6	0.6	3.8	-0.4
Slovakia	0.9	1.2	2.0	-0.6
UK	15.7	2.1	3.2	-0.2
Japan	5.8	-0.6	2.4	0.0
Austria	1.5	0.9	1.7	-0.3

5 Conclusions

First, we must emphasize that our investigations are illustrative because we only studied fossil fuel, gas flaring, and cement production emissions (the zero-order approach is the exception, where we used all of the greenhouse gases mentioned in the Kyoto Protocol). If we take into account the sum net emissions, the results would vary for the different Annex I Countries. The only common difference is that the verification conditions would be worse because the overall uncertainty is about two times greater than for the considered CO_2 sources.

The objectives of this study were to:

- investigate the appropriateness of the conditions under which the Kyoto Protocol is implemented;
- develop a VT concept of the second-order as well as for relative uncertainties directly;

- calculate the VT for Annex I countries as a business-as-usual case (using 1990–1996 data); and
- investigate the physical properties of the countries' FF systems to deduce their ability to reach Kyoto targets and verify the corresponding change in emissions.

On average, Annex I Parties to the Kyoto Protocol must reduce their emissions of greenhouse gases by 5.2% in the Kyoto commitment period (2008–2012) compared to 1990. The critical relative uncertainty is a value of about the same order, but the relative uncertainty of emission estimates of the industrialized countries is about 20%. Thus, none one of the Annex I Parties can verify a change in their emissions without the use of a special technique.

Our investigations of the critical relative uncertainty show that a direct comparison of the emissions of greenhouse gases in the base year and in the target year, as mentioned in the Kyoto Protocol, cannot be implemented successfully because uncertainties in the emission estimates are greater than the value that the Annex I Parties to the Kyoto Protocol must change (reduce) their emissions. Under these circumstances, we cannot definitely say that the target is reached or even that the emissions are changed, i.e., the Parties are in unfavorable verification conditions. We also do not believe that the uncertainties in emission estimates will be substantially reduced by the Kyoto commitment period and, in general, it is hard to achieve a little uncertainty (<5%) for a complex not well-studied system. Thus, it is necessary to develop advanced methods to control the fulfillment of the Kyoto commitments.

The application of the developed second-order VT concept for relative uncertainties reveals that all Annex I countries could potentially verify a change in their CO_2 emissions from fossil fuel combustion, gas flaring, and cement production (FF emissions, business-as-usual case).

According to our study of the physical properties of the countries' FF systems and applying the VT concept, 18 of the 26 investigated Annex I countries' FF systems can physically reach their Kyoto targets within the Kyoto commitment period. If we use softer rules, the number of successful countries increases to 21. Most of the 23 considered countries could potentially verify the changes in their CO_2 FF emissions by the end of the Kyoto commitment period, even if we assume a 10% uncertainty in FF CO_2 emission estimates and uncertainty not being reduced in the future. Three countries could verify the changes in their CO_2 FF emissions if we assume that uncertainty will reduce in the future.

If it is approved that the relative uncertainty in trend is in the order of 5%, as claimed by the IPCC, and if it is possible to use the uncertainty for critical relative uncertainty calculations, then some of the countries that should change their emissions to more than 5% could potentially verify the change in their emissions.

The Kyoto Protocol must be revised taking into account the uncertainties in emission estimates. The VT concept is a possible tool to control the fulfillment of the Kyoto commitments by the Parties. Thus, the VT concept requires further development in order to consider it in the context of the Kyoto Protocol implementation. The next step of the VT concept development is to make it more robust and apply for data reported to the UNFCCC secretariat by the Parties to the Kyoto Protocol.

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Appendix: Trajectory of Reaching the Kyoto Target, Corresponding VT Calculations for Different Initial Uncertainties, and Histograms of the First and Second Derivatives for Annex I Countries

The calculations described in Section 3.4 are visualized in the following Figures. The remarks used in the Figures are:

$dF/dt(1996)$, $d^2F/dt^2(1996)$ — first and second derivatives of the fitting polynomial in year 1996, respectively;

Fit Err — relative error fitting, which is calculated as the square root of the sum of squares of the differences between data and regression relative to the emission level in the base year (a year from which the trajectory is drawn: 1990–1993);

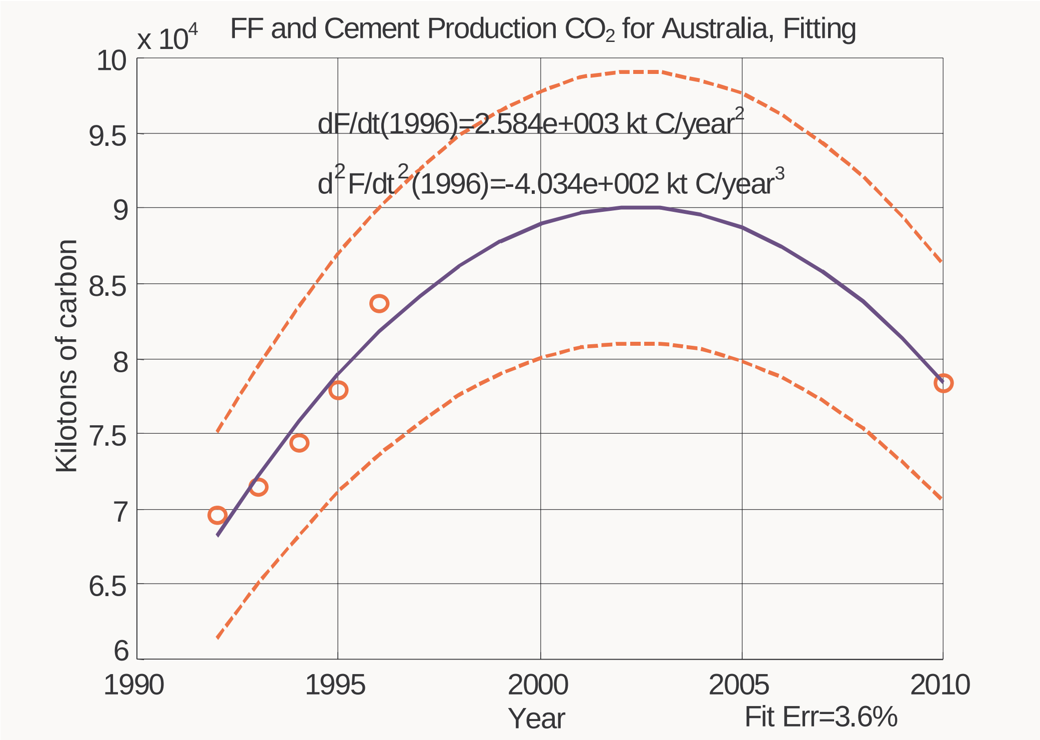
rel.err. — initial relative uncertainty for which the VT is calculated;

dt(0) — VT for the corresponding initial relative uncertainty (R’=0), from 1996;

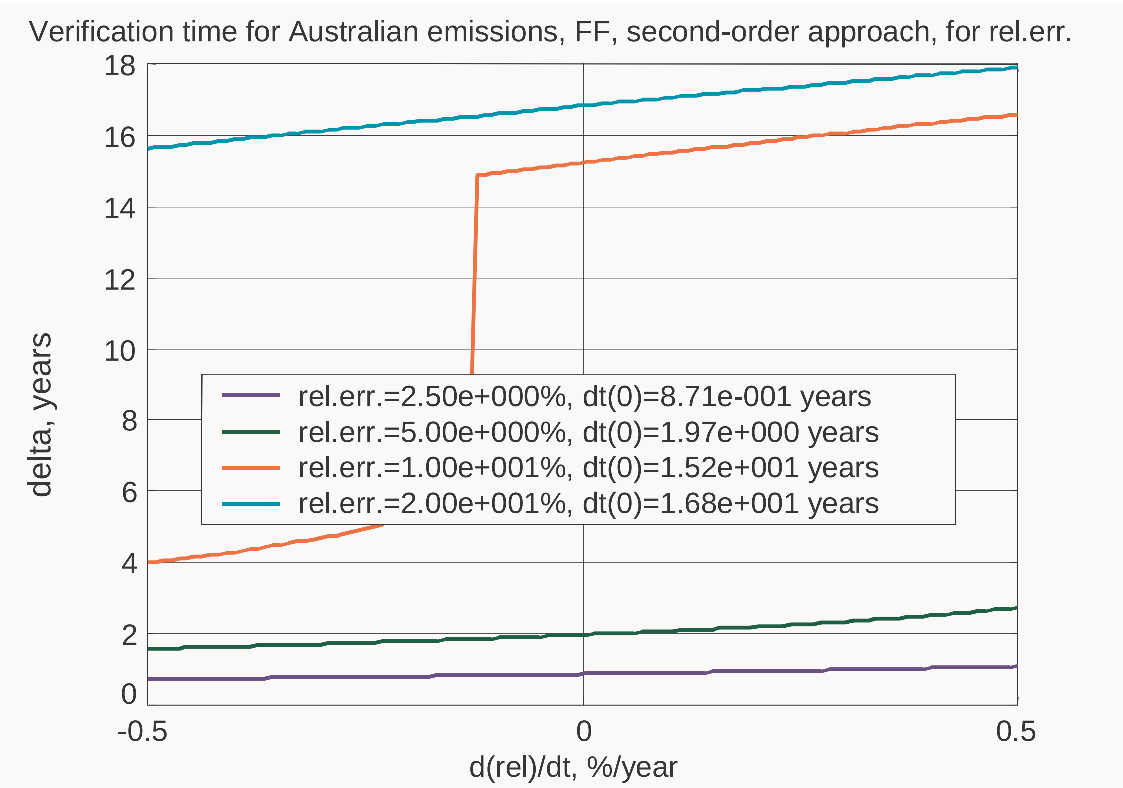
delta t — VT in years after 1996; ND

d(rel)/dt — rate of the relative uncertainty change in % per year.

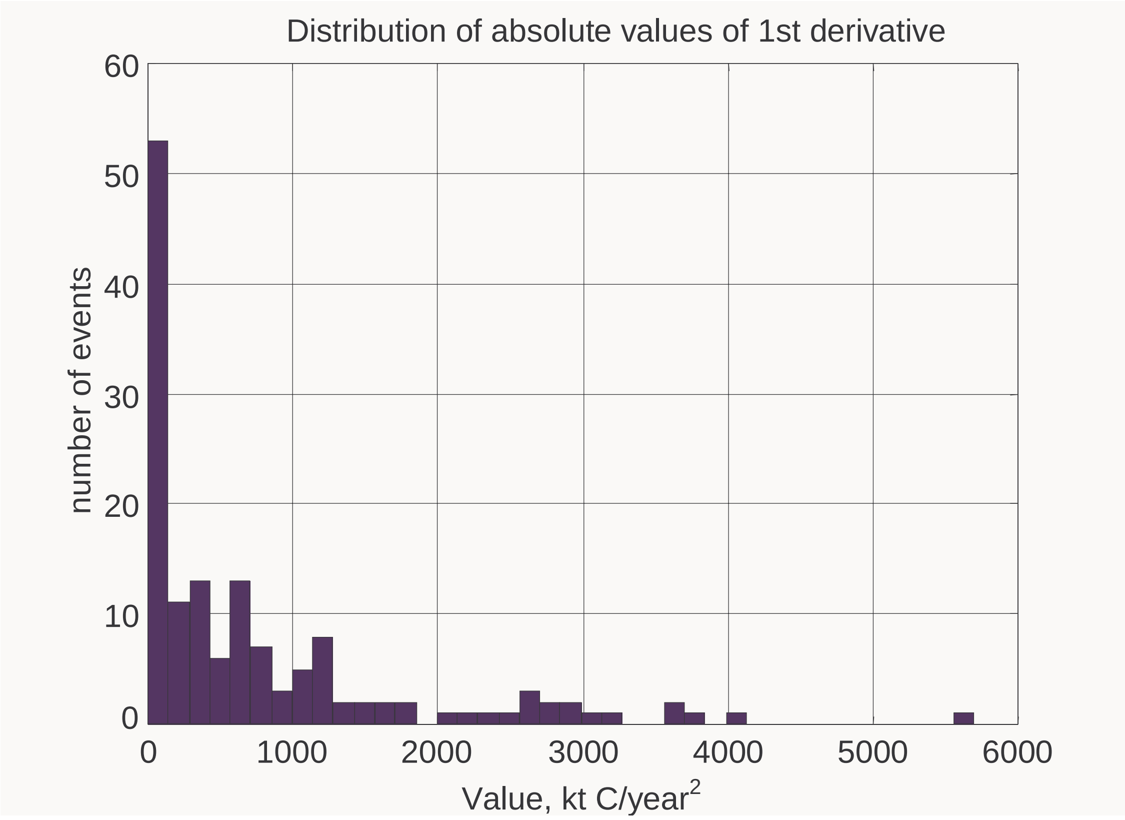
Australia

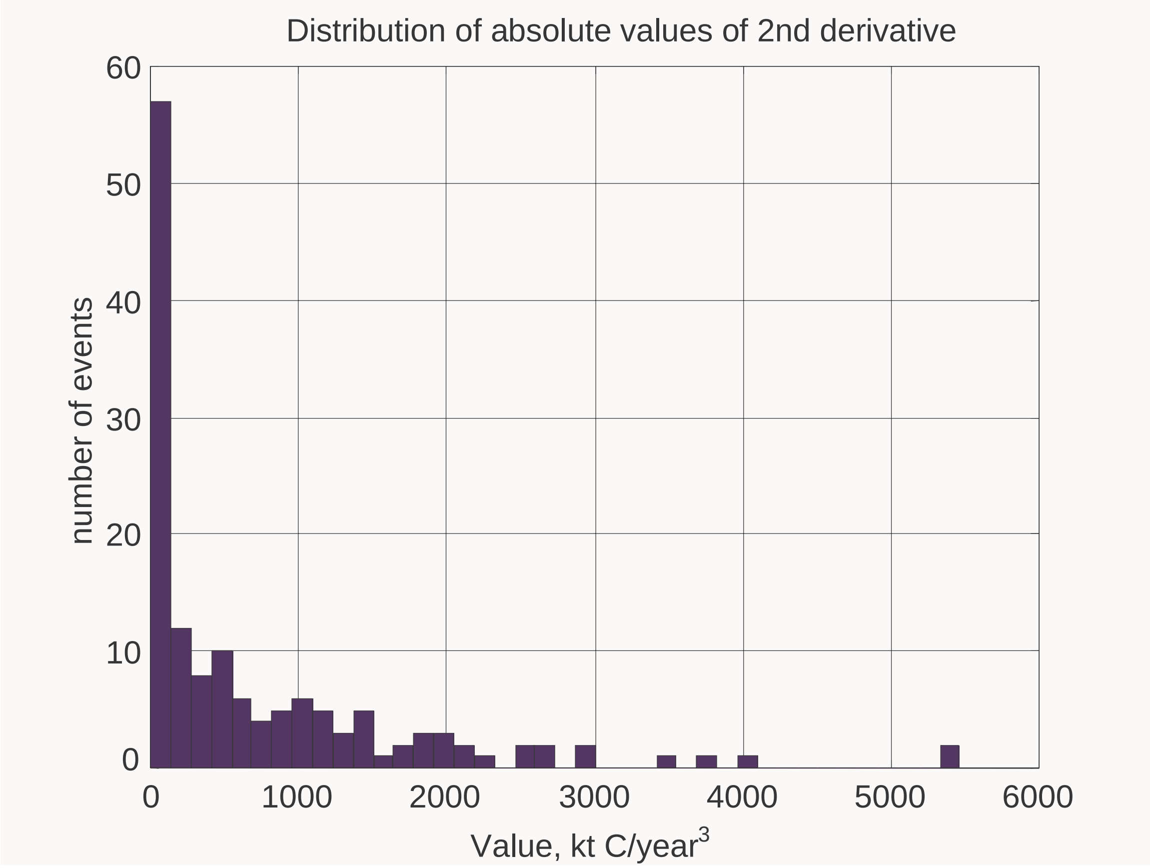


FF and Cement Production CO2 for Australia, Fitting
x 10^4
dF/dt(1996)=2.584e+003 kt C/year^2
d^2F/dt^2(1996)=-4.034e+002 kt C/year^3
Kilotons of carbon
10
9.5
9
8.5
8
7.5
7
6.5
6
1990
1995
2000
2005
2010
Year
Fit Err=3.6%

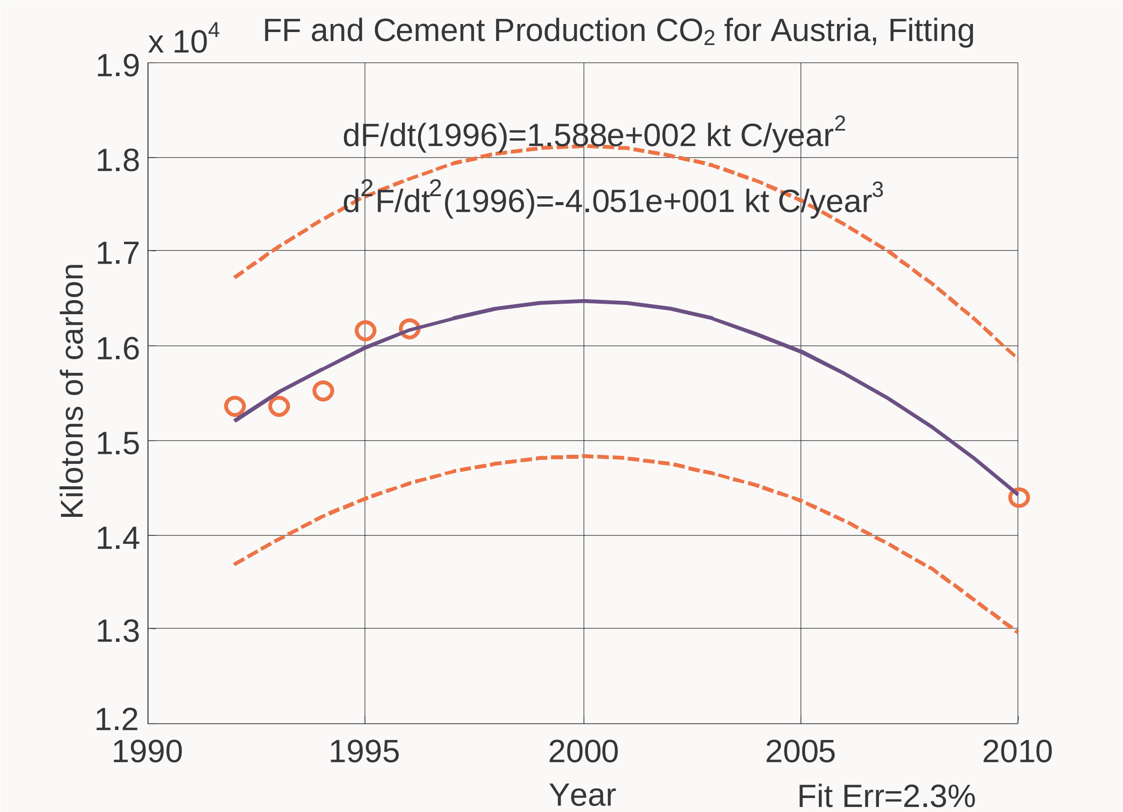


Verification time for Australian emissions, FF, second-order approach, for rel.err.
delta, years
18
16
14
12
10
8
6
4
2
0
-0.5
0
0.5
d(rel)/dt, %/year
rel.err.=2.50e+000%, dt(0)=8.71e-001 years
rel.err.=5.00e+000%, dt(0)=1.97e+000 years
rel.err.=1.00e+001%, dt(0)=1.52e+001 years
rel.err.=2.00e+001%, dt(0)=1.68e+001 years

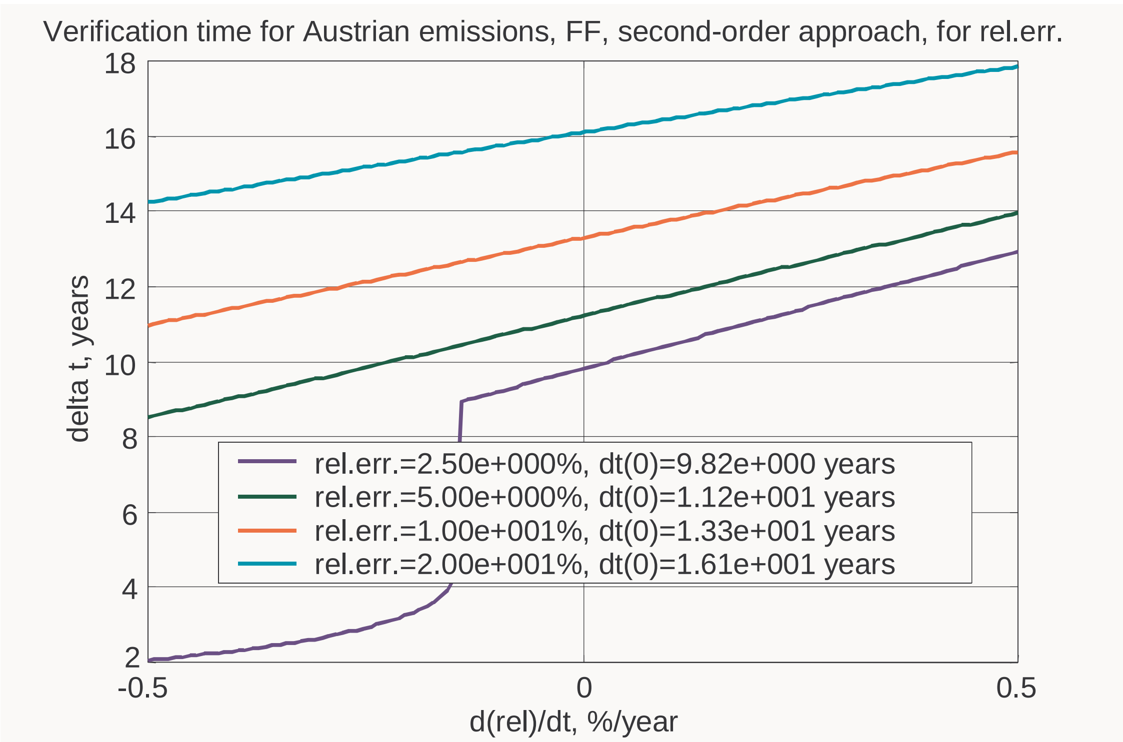

Distribution of absolute values of 1st derivative
number of events
60
50
40
30
20
10
0
0
1000
2000
3000
4000
5000
6000
Value, kt C/year2


Distribution of absolute values of 2nd derivative
number of events
60
50
40
30
20
10
0
0
1000
2000
3000
4000
5000
6000
Value, kt C/year3

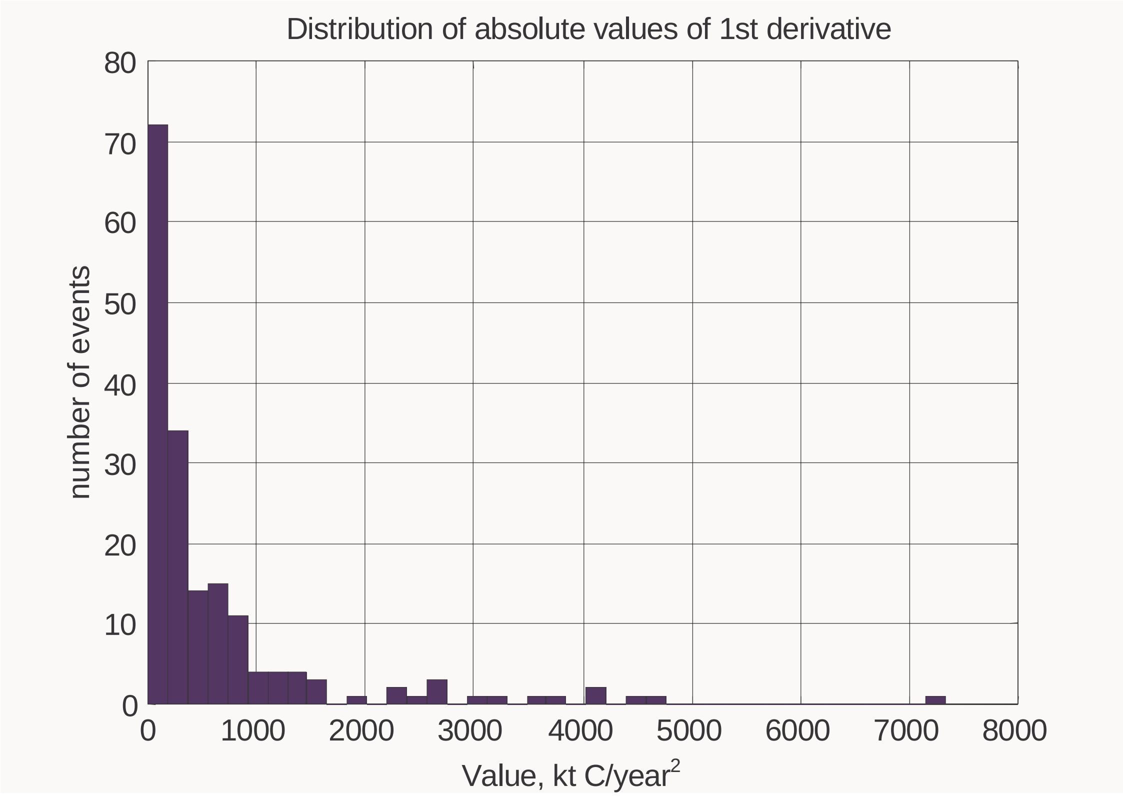
Austria

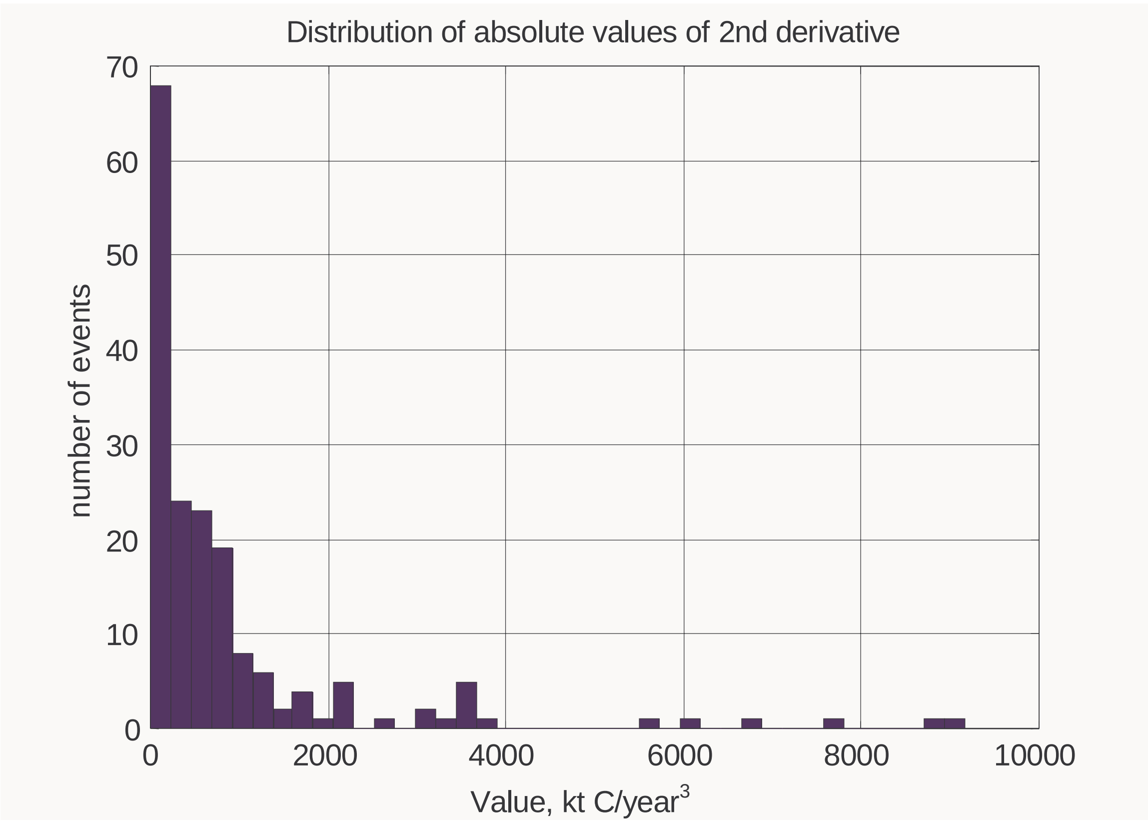


FF and Cement Production CO2 for Austria, Fitting
x 10^4
dF/dt(1996)=1.588e+002 kt C/year^2
d^2F/dt^2(1996)=-4.051e+001 kt C/year^3
Kilotons of carbon
1.9
1.8
1.7
1.6
1.5
1.4
1.3
1.2
1990
1995
2000
2005
2010
Year
Fit Err=2.3%

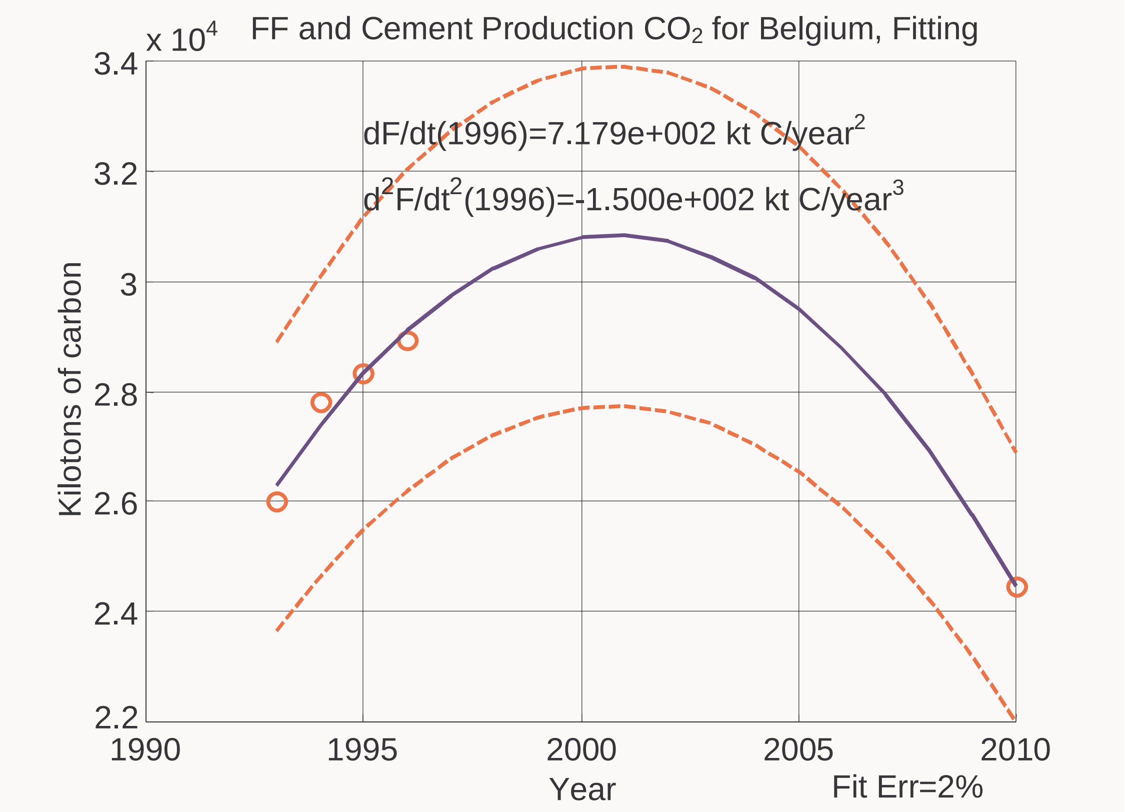


Verification time for Austrian emissions, FF, second-order approach, for rel.err.
delta t, years
18
16
14
12
10
8
6
4
2
-0.5
0
0.5
d(rel)/dt, %/year
rel.err.=2.50e+000%, dt(0)=9.82e+000 years
rel.err.=5.00e+000%, dt(0)=1.12e+001 years
rel.err.=1.00e+001%, dt(0)=1.33e+001 years
rel.err.=2.00e+001%, dt(0)=1.61e+001 years

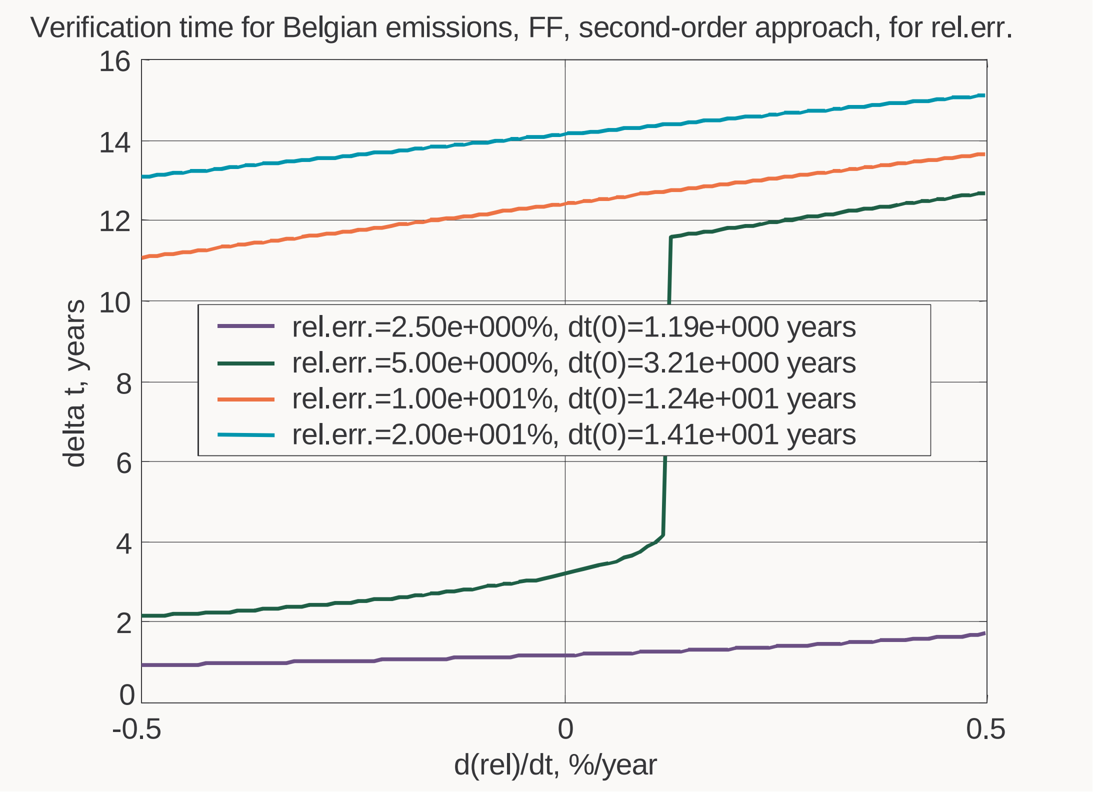

Distribution of absolute values of 1st derivative
number of events
0
10
20
30
40
50
60
70
80
0
1000
2000
3000
4000
5000
6000
7000
8000
Value, kt C/year2


Distribution of absolute values of 2nd derivative
number of events
0
10
20
30
40
50
60
70
0
2000
4000
6000
8000
10000
Value, kt C/year3

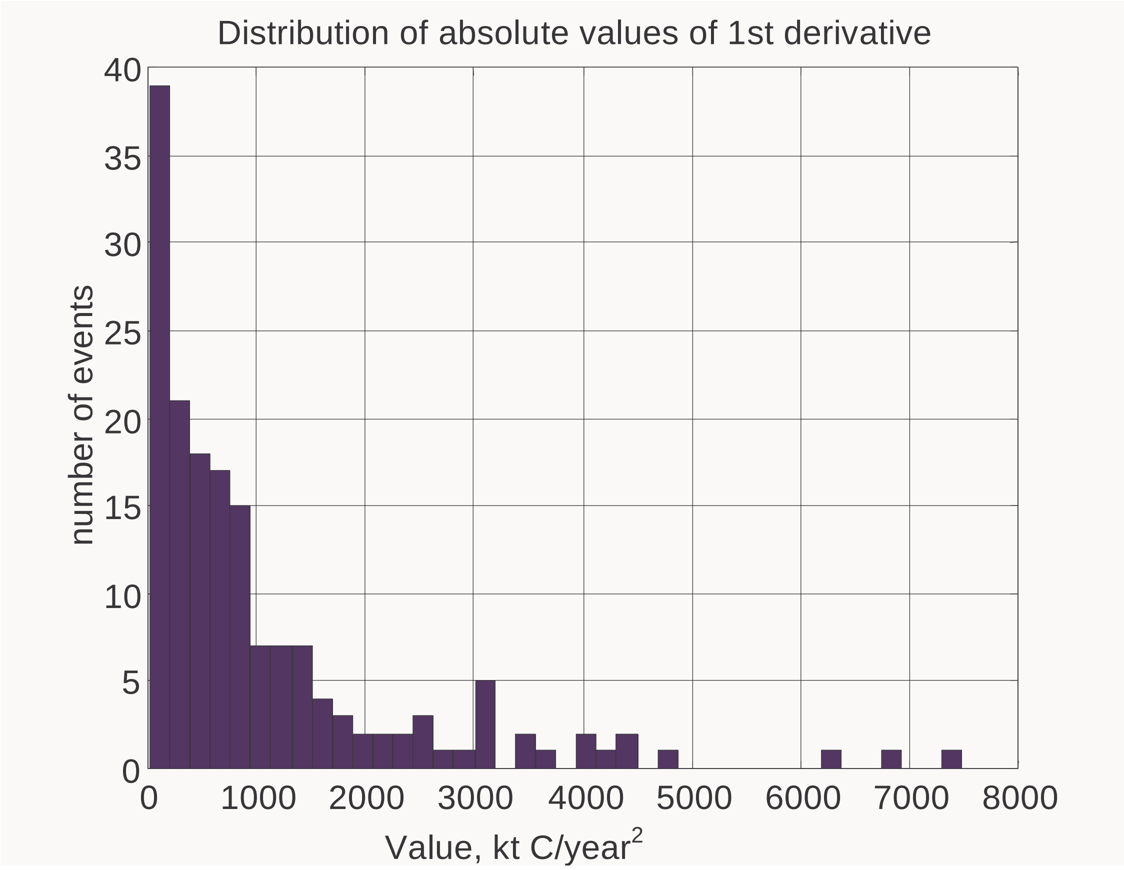
Belgium

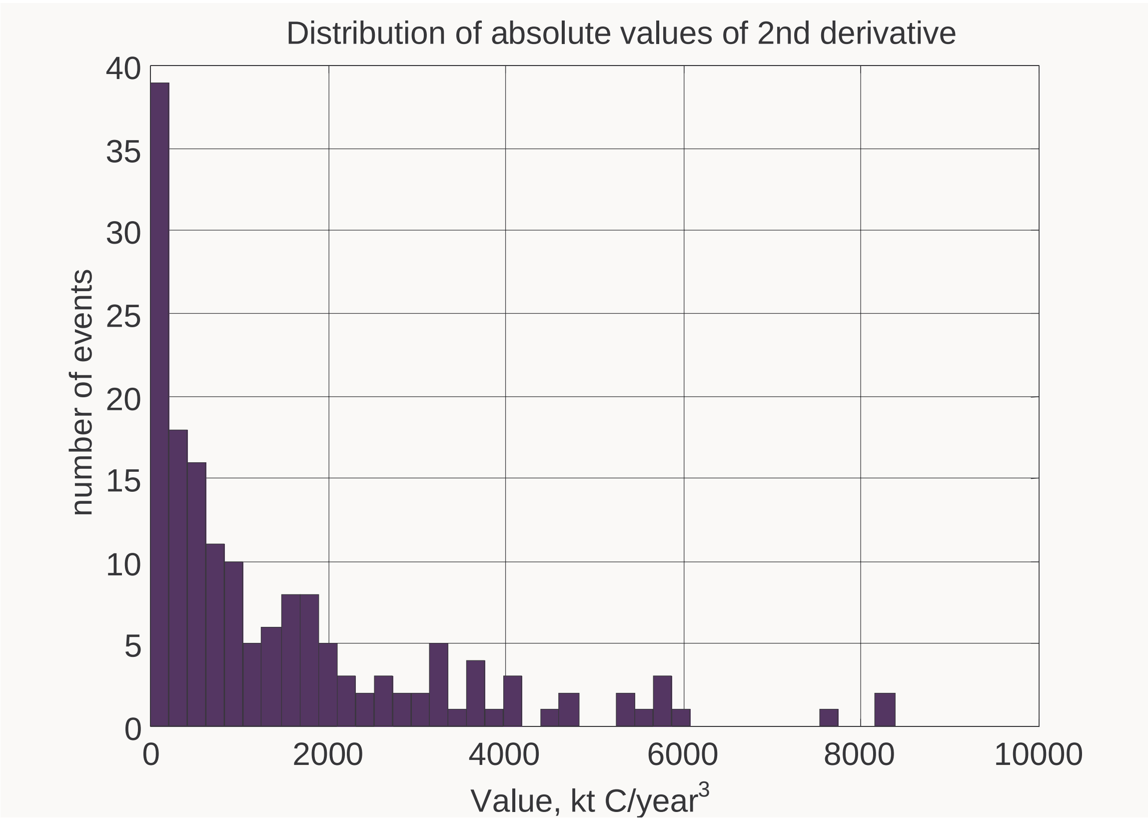


x 10^4
FF and Cement Production CO2 for Belgium, Fitting
dF/dt(1996)=7.179e+002 kt C/year^2
d^2F/dt^2(1996)=-1.500e+002 kt C/year^3
Kilotons of carbon
3.4
3.2
3
2.8
2.6
2.4
2.2
1990
1995
2000
2005
2010
Year
Fit Err=2%

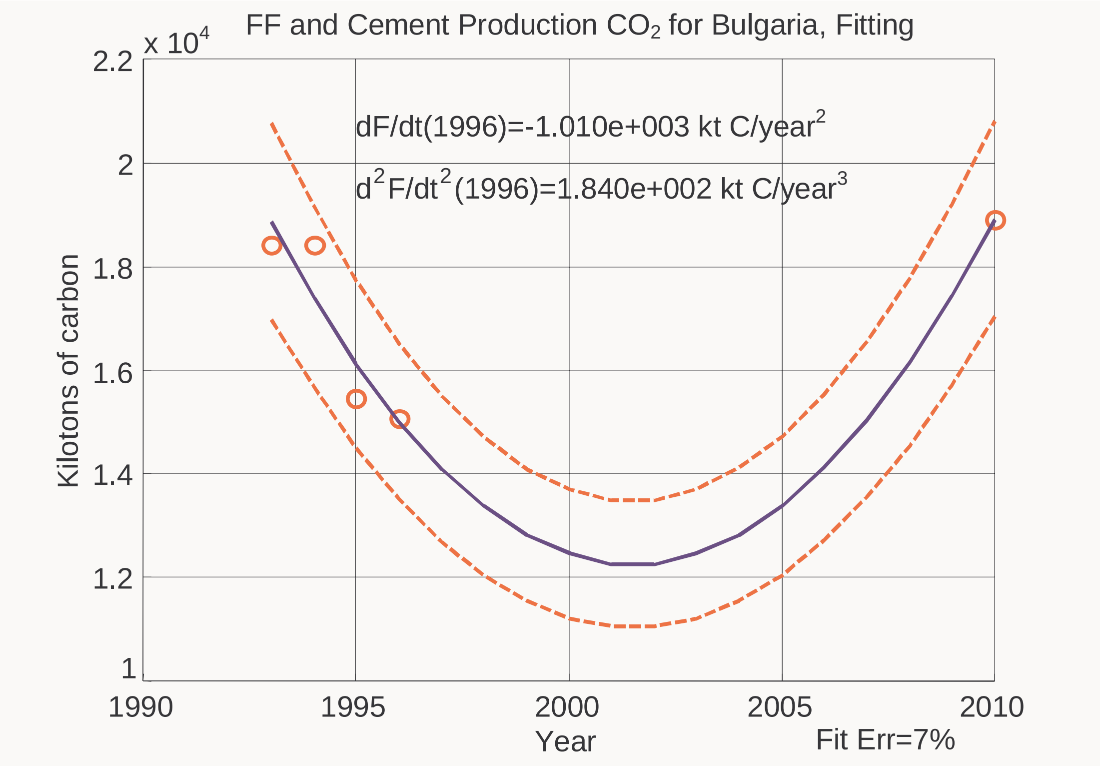


Verification time for Belgian emissions, FF, second-order approach, for rel.err.
delta t, years
16
14
12
10
8
6
4
2
0
-0.5
0
0.5
d(rel)/dt, %/year
rel.err.=2.50e+000%, dt(0)=1.19e+000 years
rel.err.=5.00e+000%, dt(0)=3.21e+000 years
rel.err.=1.00e+001%, dt(0)=1.24e+001 years
rel.err.=2.00e+001%, dt(0)=1.41e+001 years

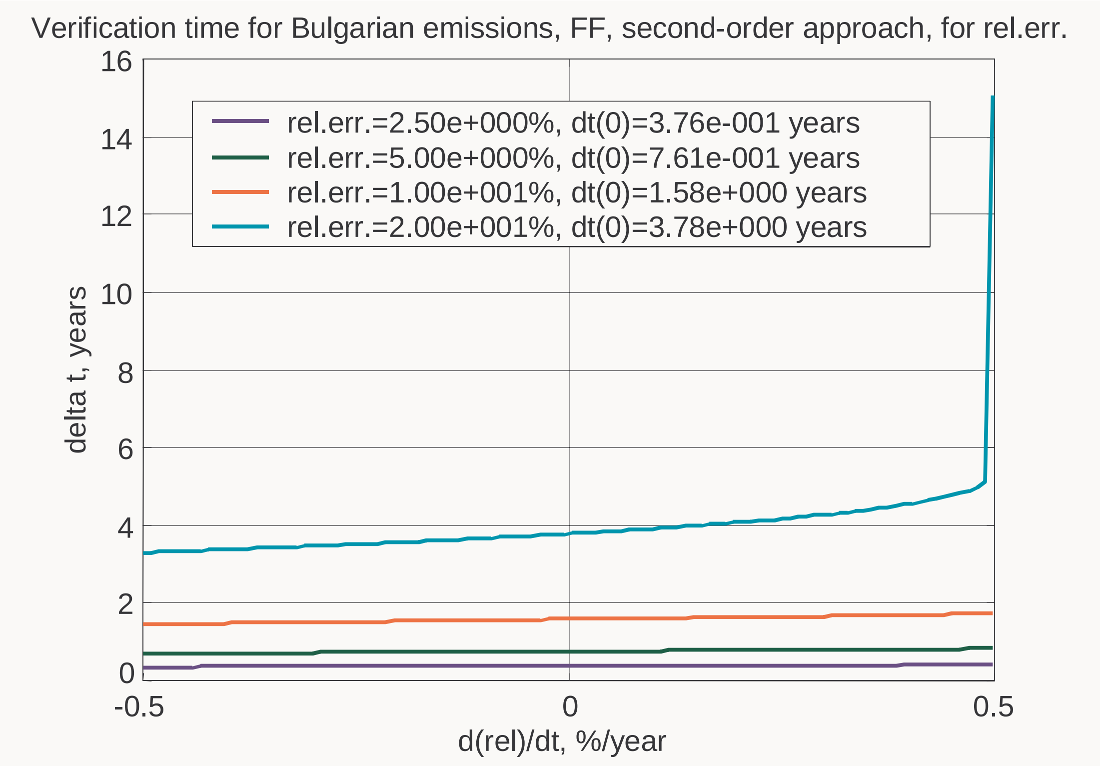

Distribution of absolute values of 1st derivative
number of events
0
5
10
15
20
25
30
35
40
0
1000
2000
3000
4000
5000
6000
7000
8000
Value, kt C/year^2


Distribution of absolute values of 2nd derivative
number of events
0
5
10
15
20
25
30
35
40
0
2000
4000
6000
8000
10000
Value, kt C/year^3

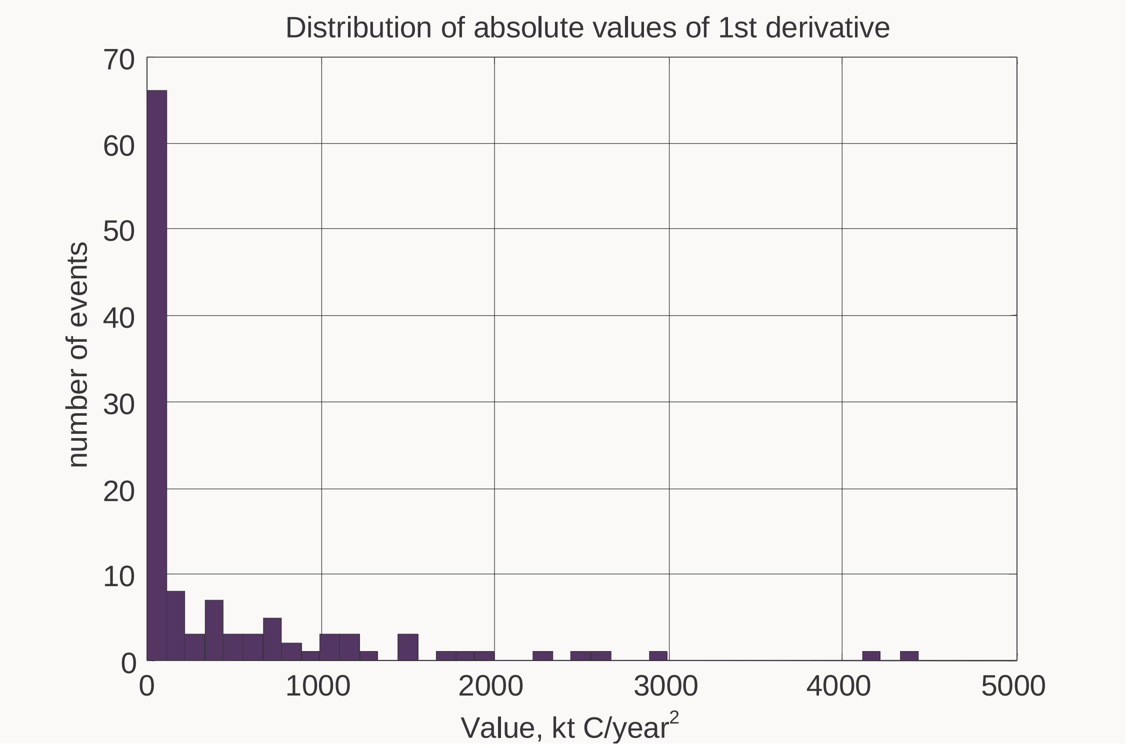
Bulgaria

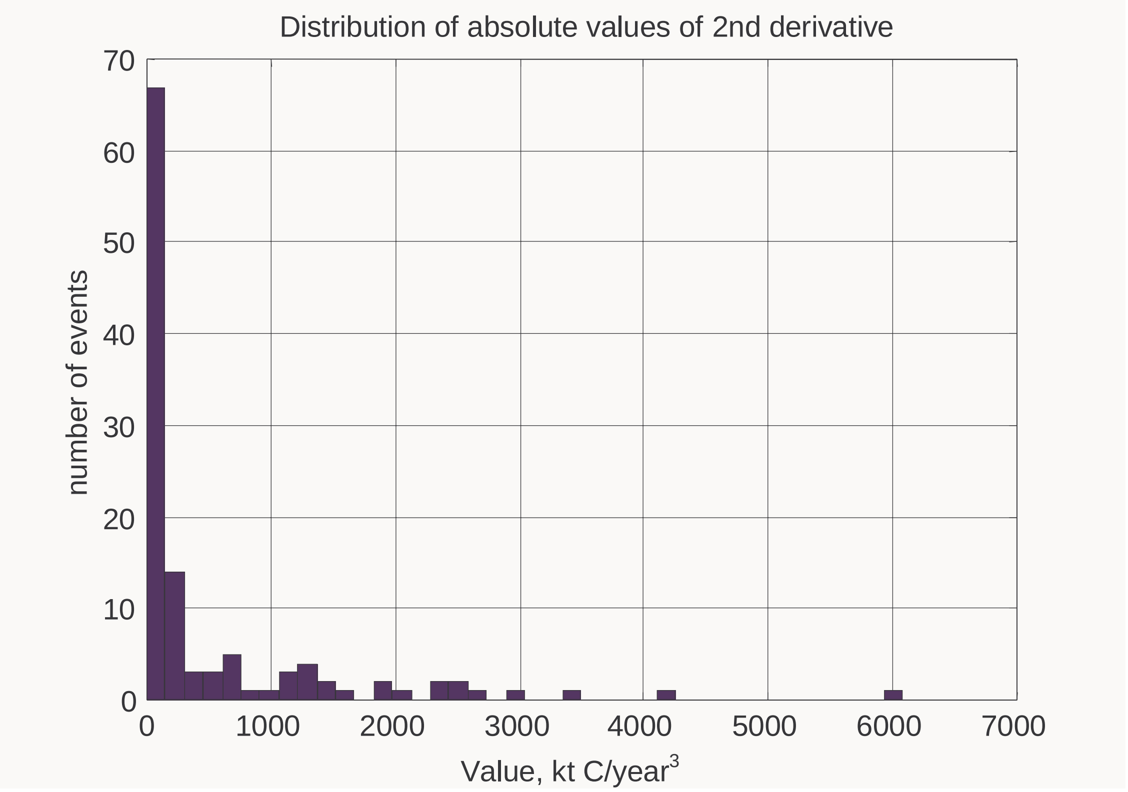


FF and Cement Production CO_2 for Bulgaria, Fitting
x 10^4
dF/dt(1996)=-1.010e+003 kt C/year^2
d^2F/dt^2(1996)=1.840e+002 kt C/year^3
Kilotons of carbon
2.2
2
1.8
1.6
1.4
1.2
1
1990
1995
2000
2005
2010
Year
Fit Err=7%

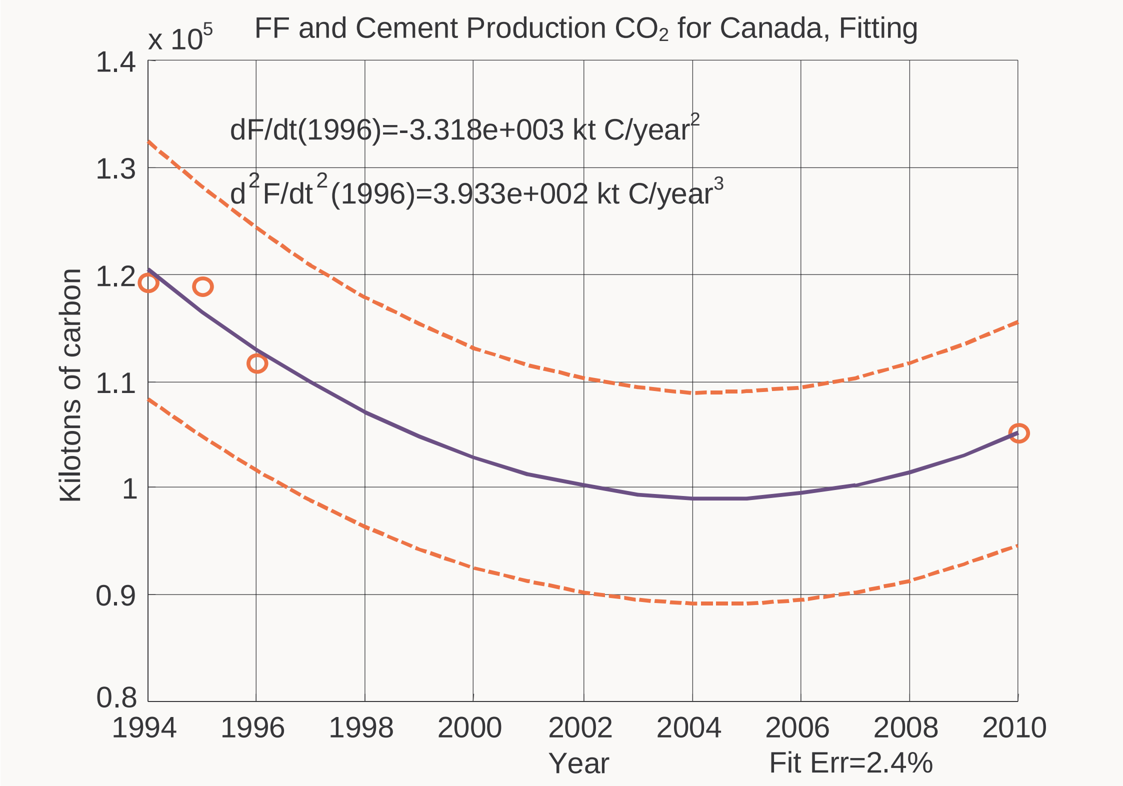


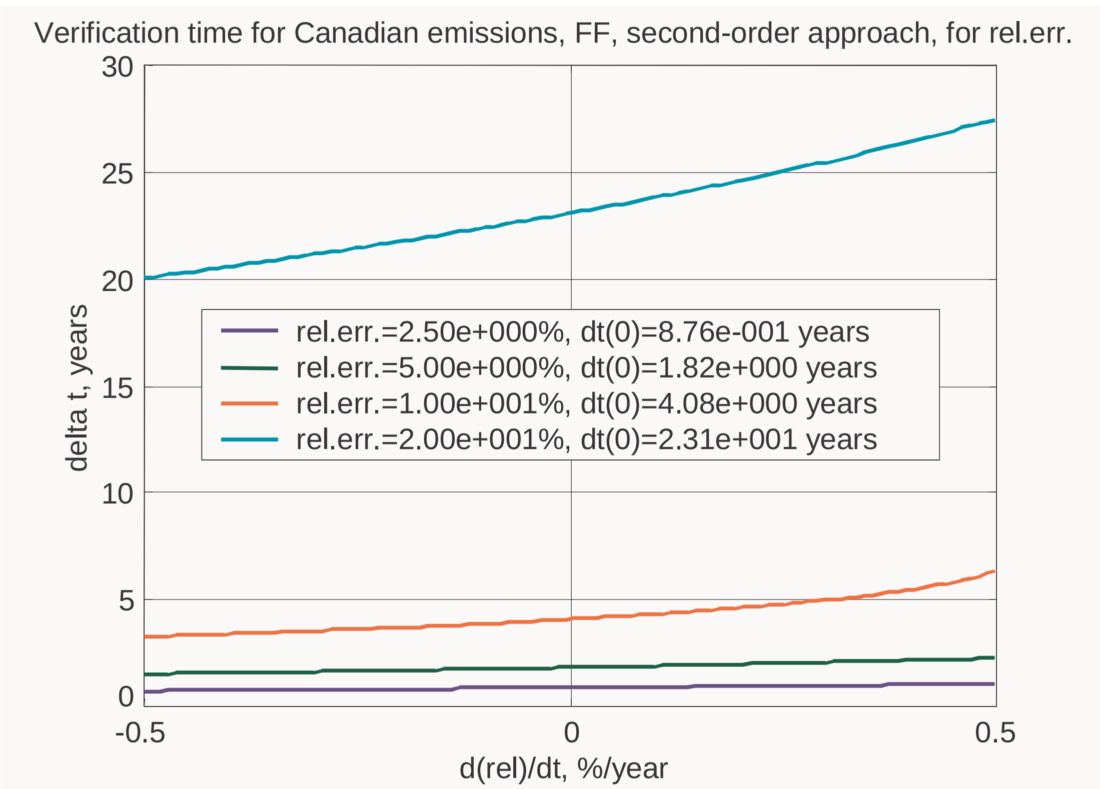
Verification time for Bulgarian emissions, FF, second-order approach, for rel.err.
rel.err.=2.50e+000%, dt(0)=3.76e-001 years
rel.err.=5.00e+000%, dt(0)=7.61e-001 years
rel.err.=1.00e+001%, dt(0)=1.58e+000 years
rel.err.=2.00e+001%, dt(0)=3.78e+000 years
delta t, years
16
14
12
10
8
6
4
2
0
-0.5
0
0.5
d(rel)/dt, %/year

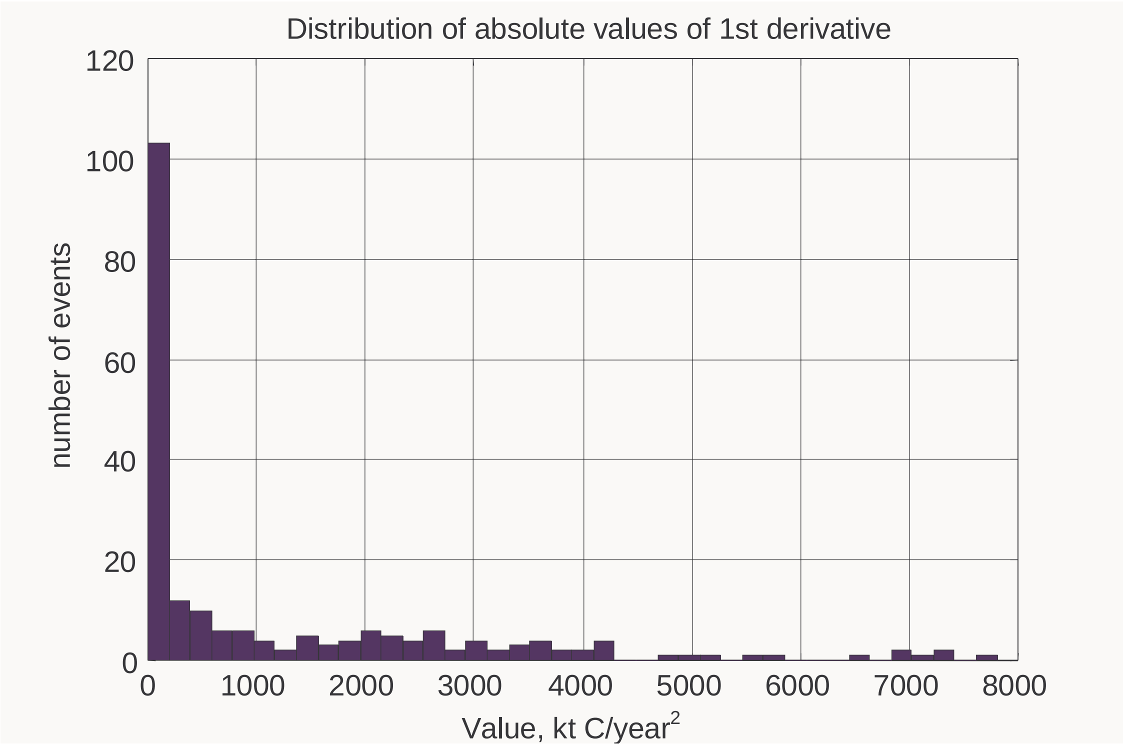

Distribution of absolute values of 1st derivative
number of events
0
10
20
30
40
50
60
70
0
1000
2000
3000
4000
5000
Value, kt C/year2


Distribution of absolute values of 2nd derivative
number of events
0
10
20
30
40
50
60
70
0
1000
2000
3000
4000
5000
6000
7000
Value, kt C/year3

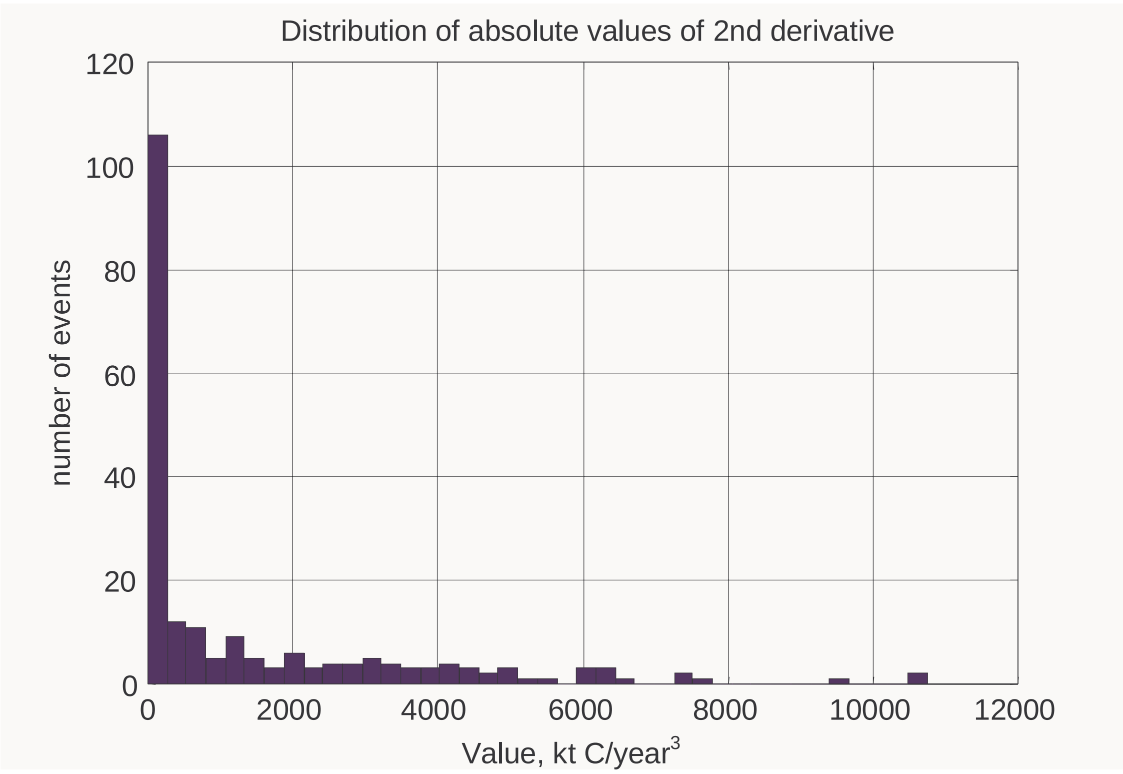
Canada


FF and Cement Production CO_2 for Canada, Fitting
x 10^5
dF/dt(1996)=-3.318e+003 kt C/year^2
d^2F/dt^2(1996)=3.933e+002 kt C/year^3
Kilotons of carbon
1.4
1.3
1.2
1.1
1
0.9
0.8
1994
1996
1998
2000
2002
2004
2006
2008
2010
Year
Fit Err=2.4%


Verification time for Canadian emissions, FF, second-order approach, for rel.err.
delta t, years
30
25
20
15
10
5
0
rel.err.=2.50e+000%, dt(0)=8.76e-001 years
rel.err.=5.00e+000%, dt(0)=1.82e+000 years
rel.err.=1.00e+001%, dt(0)=4.08e+000 years
rel.err.=2.00e+001%, dt(0)=2.31e+001 years
-0.5
0
0.5
d(rel)/dt, %/year

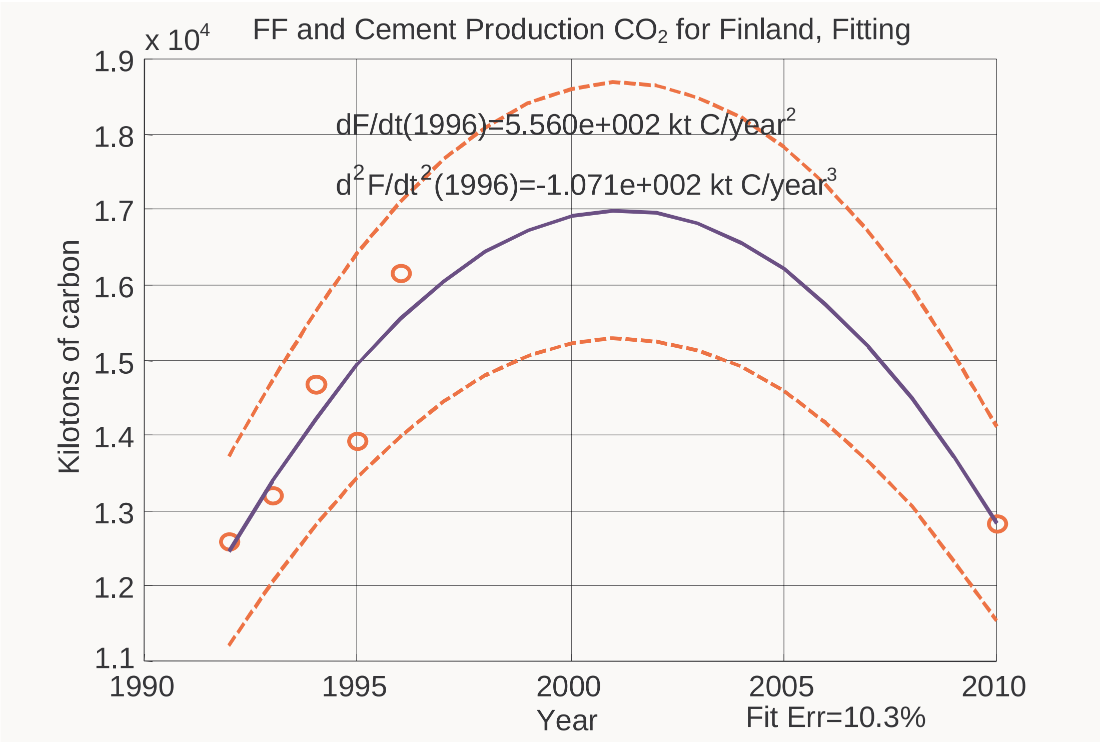


Distribution of absolute values of 1st derivative
number of events
0
20
40
60
80
100
120
0
1000
2000
3000
4000
5000
6000
7000
8000
Value, kt C/year2

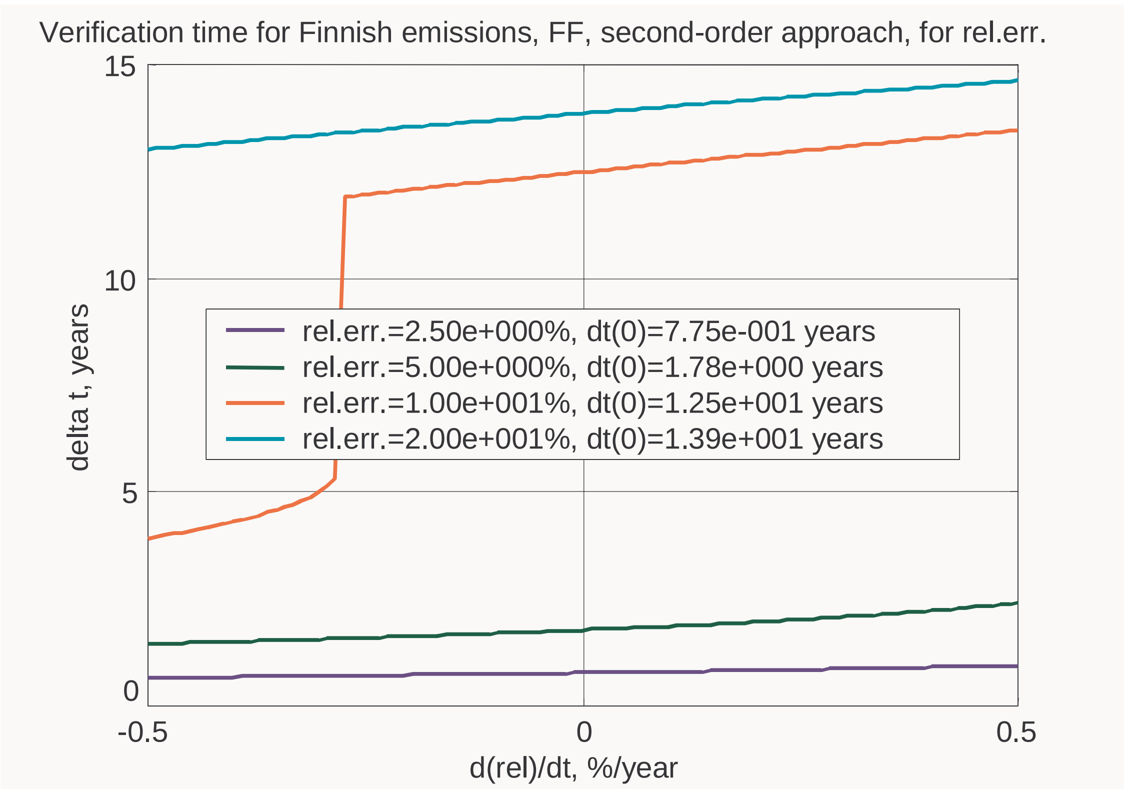


Distribution of absolute values of 2nd derivative
number of events
0
20
40
60
80
100
120
0
2000
4000
6000
8000
10000
12000
Value, kt C/year3

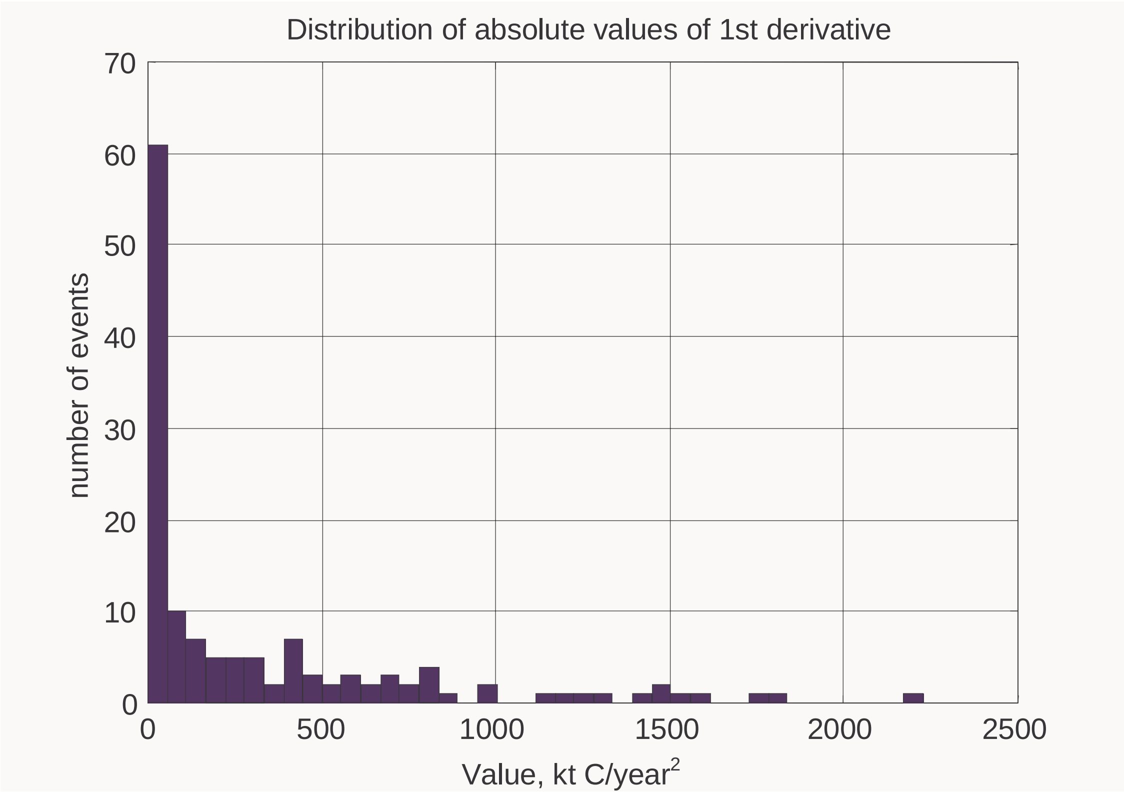
Finland

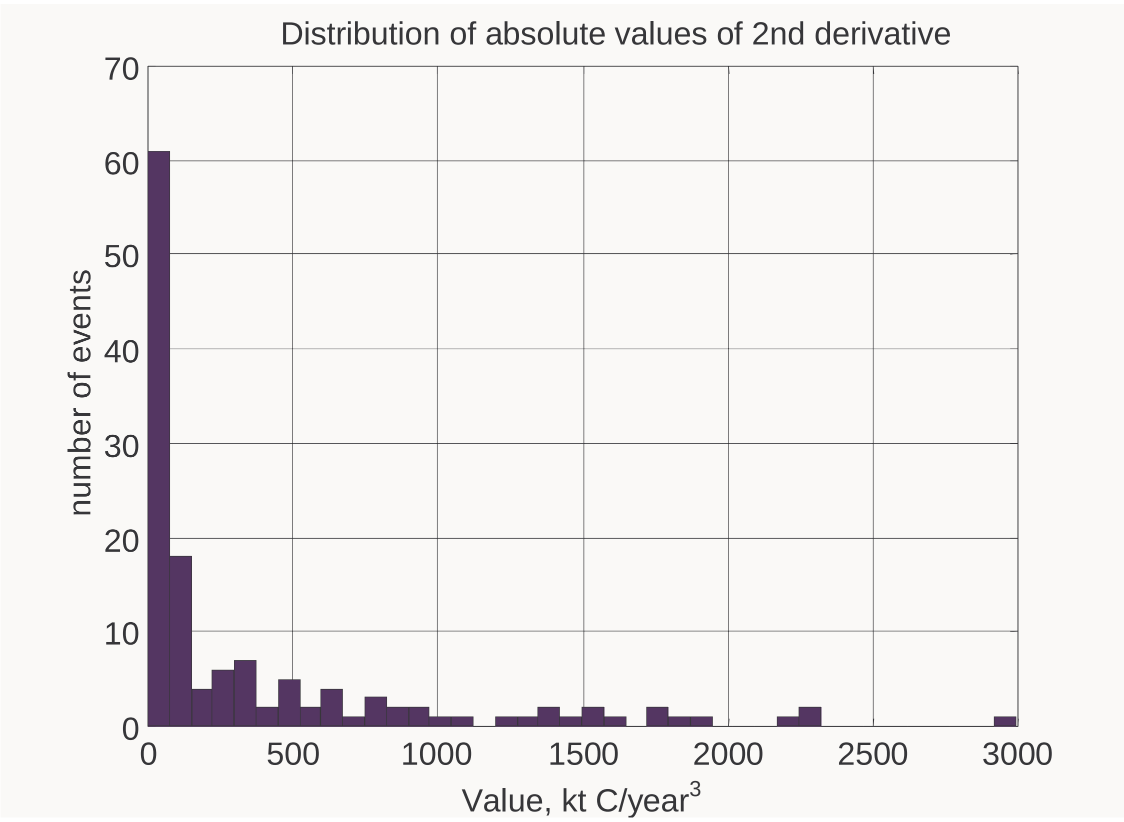


FF and Cement Production CO2 for Finland, Fitting
x 10^4
1.9
1.8
1.7
1.6
1.5
1.4
1.3
1.2
1.1
Kilotons of carbon
dF/dt(1996)=5.560e+002 kt C/year^2
d^2F/dt^2(1996)=-1.071e+002 kt C/year^3
1990
1995
2000
2005
2010
Year
Fit Err=10.3%

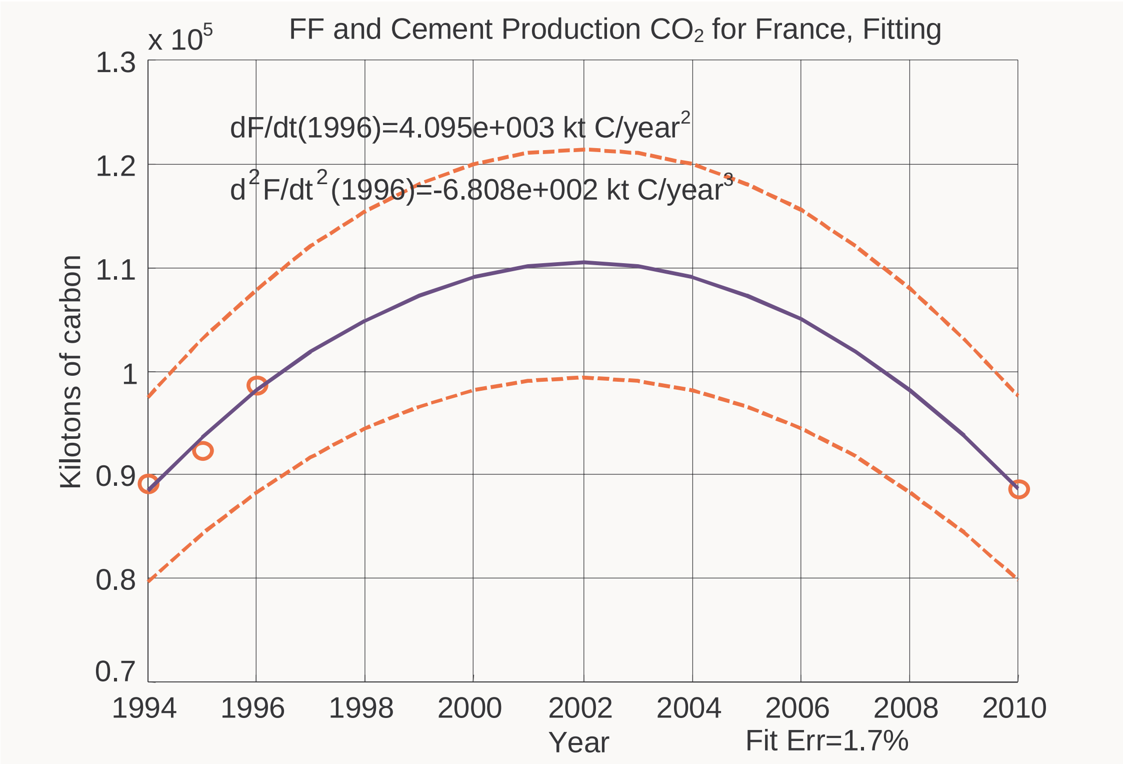


Verification time for Finnish emissions, FF, second-order approach, for rel.err.
15
10
5
0
delta t, years
rel.err.=2.50e+000%, dt(0)=7.75e-001 years
rel.err.=5.00e+000%, dt(0)=1.78e+000 years
rel.err.=1.00e+001%, dt(0)=1.25e+001 years
rel.err.=2.00e+001%, dt(0)=1.39e+001 years
-0.5
0
0.5
d(rel)/dt, %/year

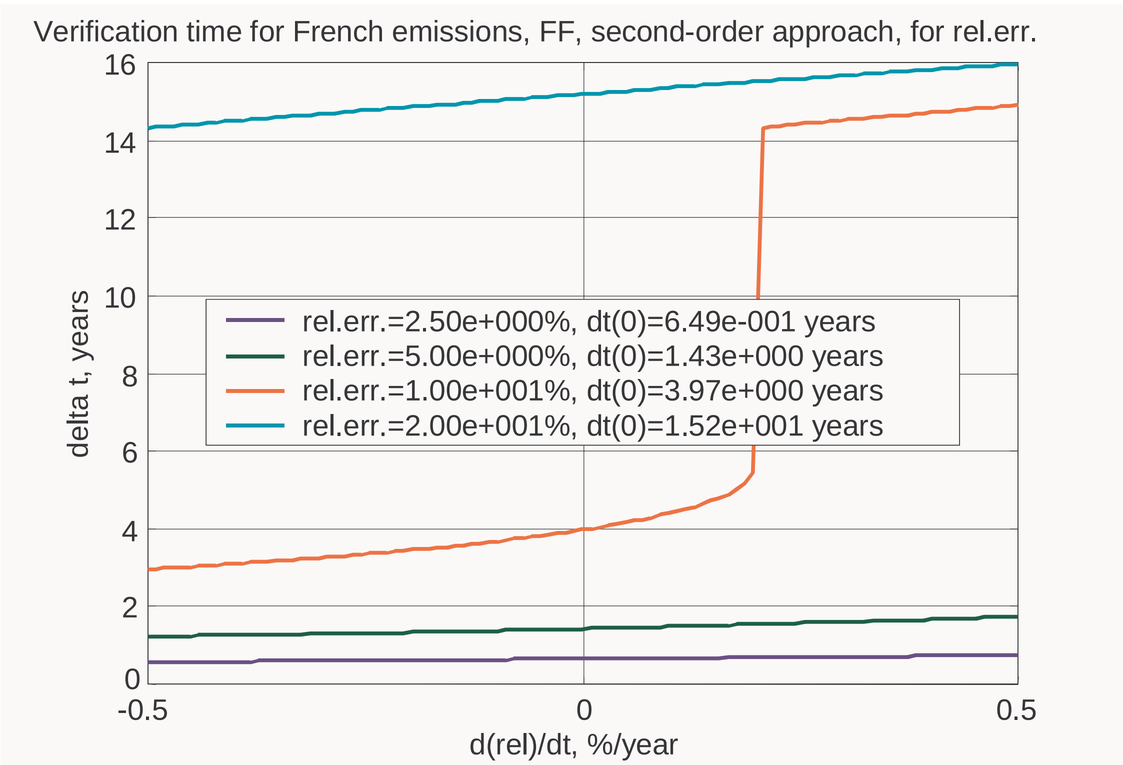

Distribution of absolute values of 1st derivative
number of events
Value, kt C/year2
0
10
20
30
40
50
60
70
0
500
1000
1500
2000
2500


Distribution of absolute values of 2nd derivative
number of events
Value, kt C/year3
0
10
20
30
40
50
60
70
0
500
1000
1500
2000
2500
3000

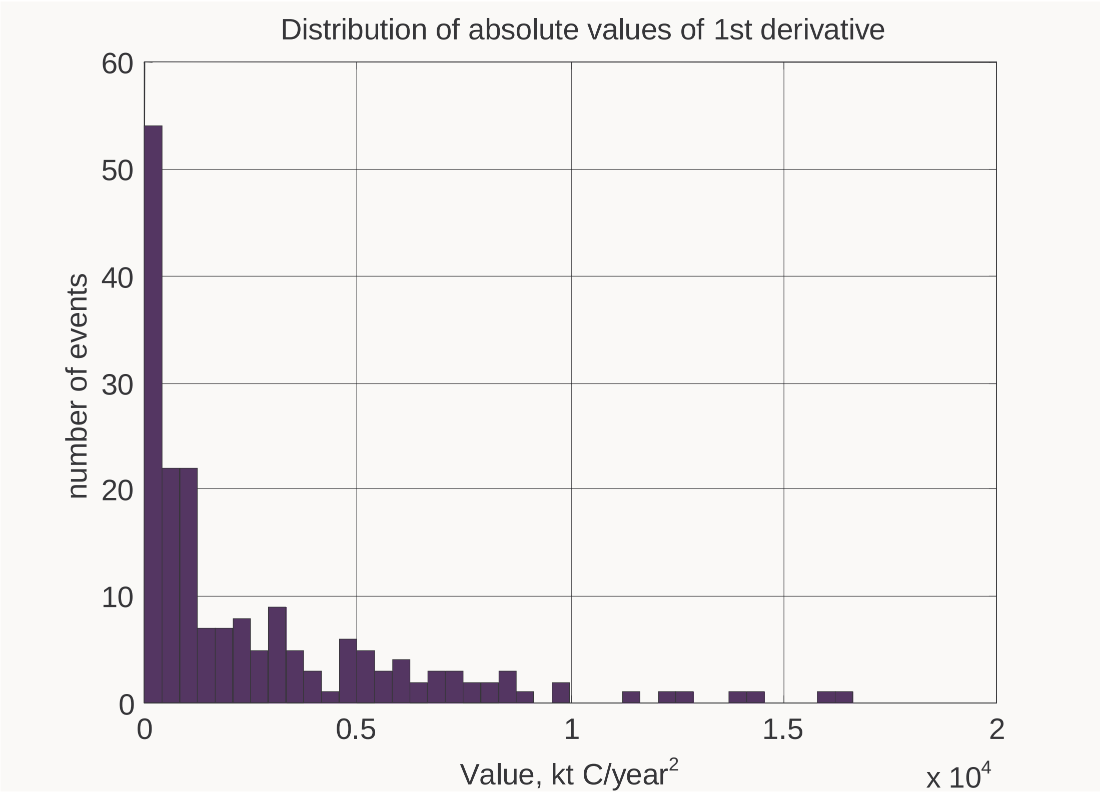
France

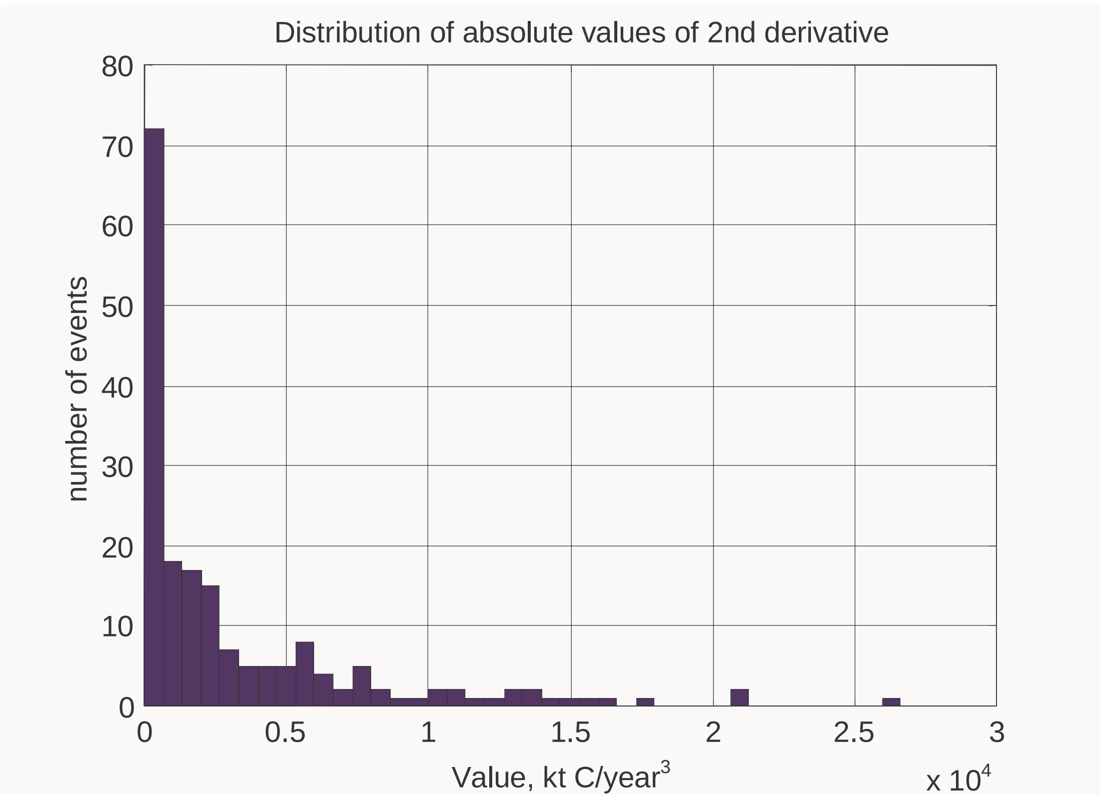


FF and Cement Production CO2 for France, Fitting
x 10^5
dF/dt(1996)=4.095e+003 kt C/year^2
d^2F/dt^2(1996)=-6.808e+002 kt C/year^3
Kilotons of carbon
1.3
1.2
1.1
1
0.9
0.8
0.7
1994
1996
1998
2000
2002
2004
2006
2008
2010
Year
Fit Err=1.7%

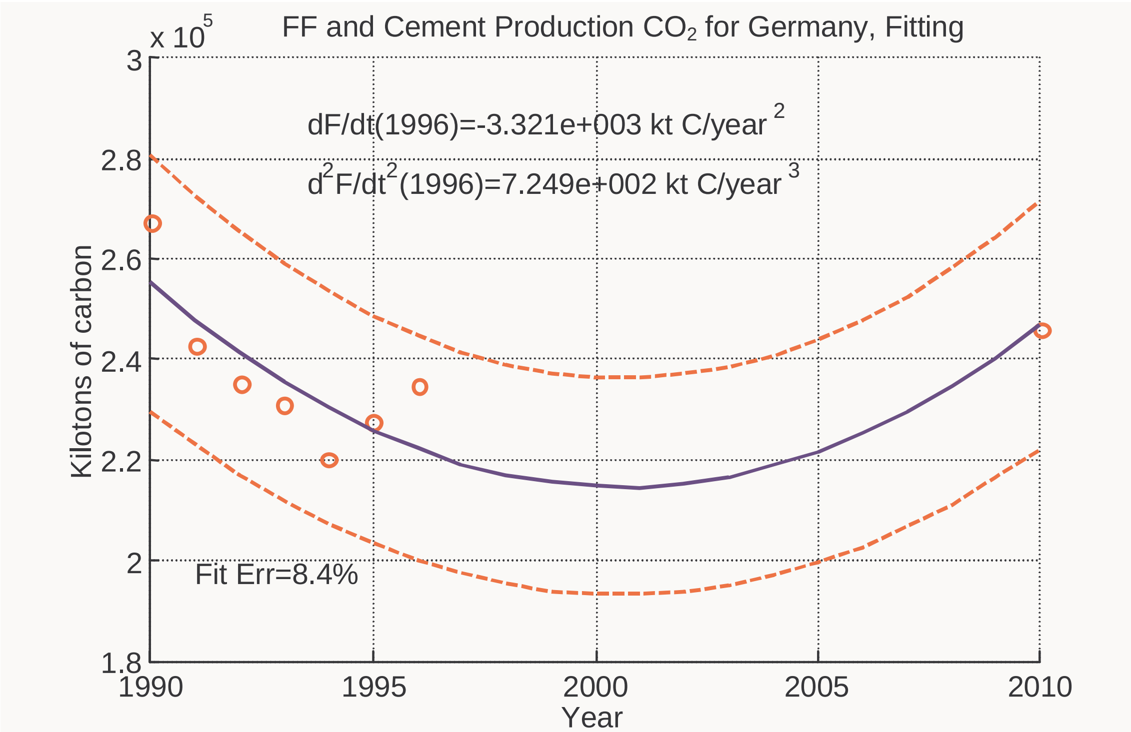


Verification time for French emissions, FF, second-order approach, for rel.err.
delta t, years
16
14
12
10
8
6
4
2
0
rel.err.=2.50e+000%, dt(0)=6.49e-001 years
rel.err.=5.00e+000%, dt(0)=1.43e+000 years
rel.err.=1.00e+001%, dt(0)=3.97e+000 years
rel.err.=2.00e+001%, dt(0)=1.52e+001 years
-0.5
0
0.5
d(rel)/dt, %/year

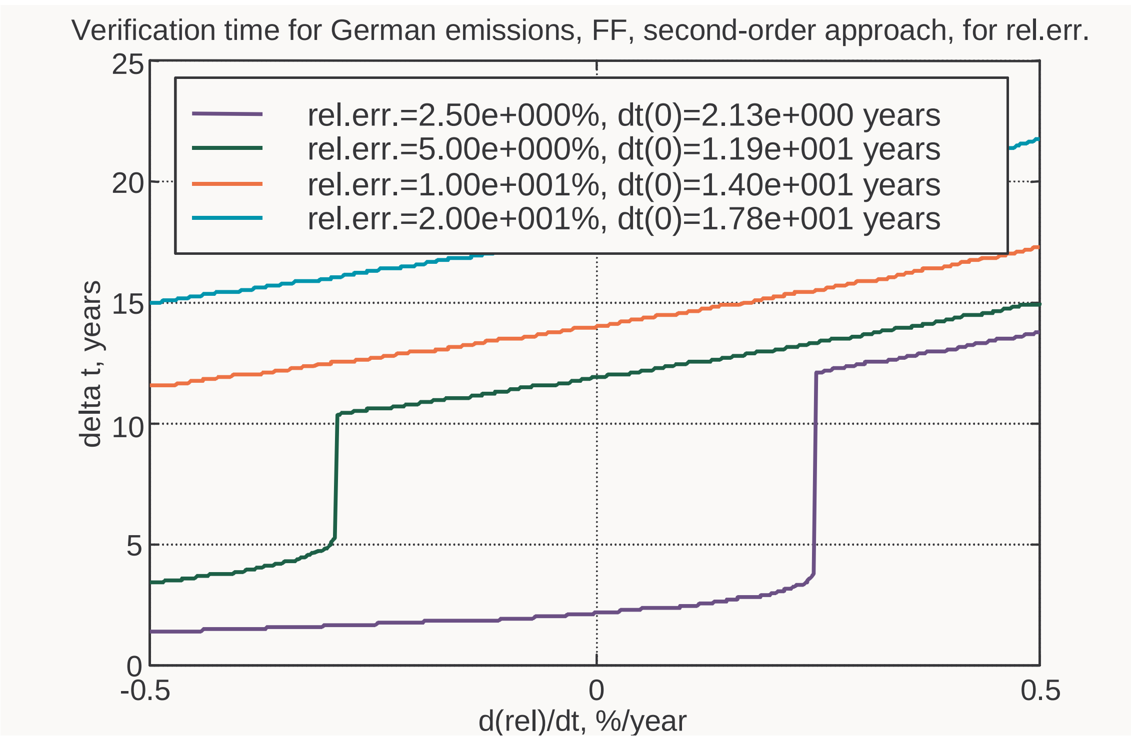

Distribution of absolute values of 1st derivative
number of events
0
10
20
30
40
50
60
0
0.5
1
1.5
2
Value, kt C/year2
x 104


Distribution of absolute values of 2nd derivative
number of events
0
10
20
30
40
50
60
70
80
0
0.5
1
1.5
2
2.5
3
Value, kt C/year3
x 104

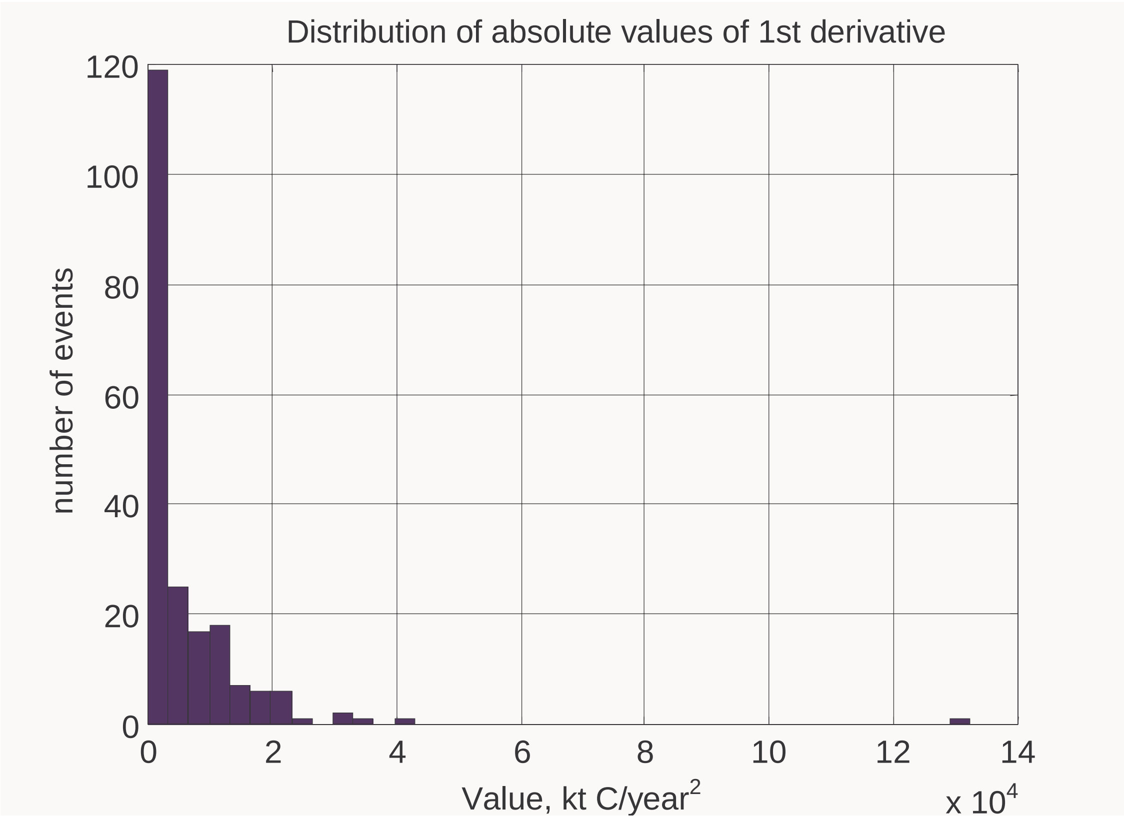
Germany



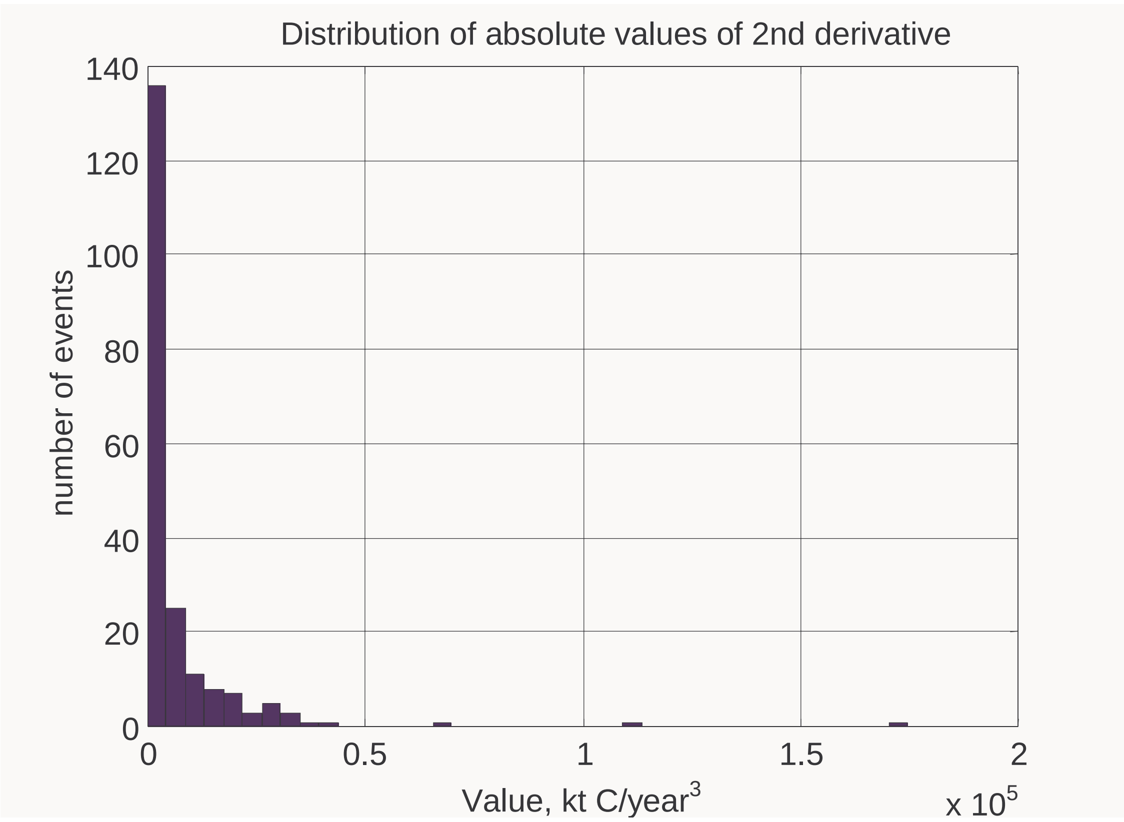
FF and Cement Production CO2 for Germany, Fitting
x 10^5
dF/dt(1996)=-3.321e+003 kt C/year 2
d2F/dt2(1996)=7.249e+002 kt C/year 3
Fit Err=8.4%
Kilotons of carbon
Year
3
2.8
2.6
2.4
2.2
2
1.8
1990
1995
2000
2005
2010



Verification time for German emissions, FF, second-order approach, for rel.err.
rel.err.=2.50e+000%, dt(0)=2.13e+000 years
rel.err.=5.00e+000%, dt(0)=1.19e+001 years
rel.err.=1.00e+001%, dt(0)=1.40e+001 years
rel.err.=2.00e+001%, dt(0)=1.78e+001 years
delta t, years
d(rel)/dt, %/year
25
20
15
10
5
0
-0.5
0
0.5

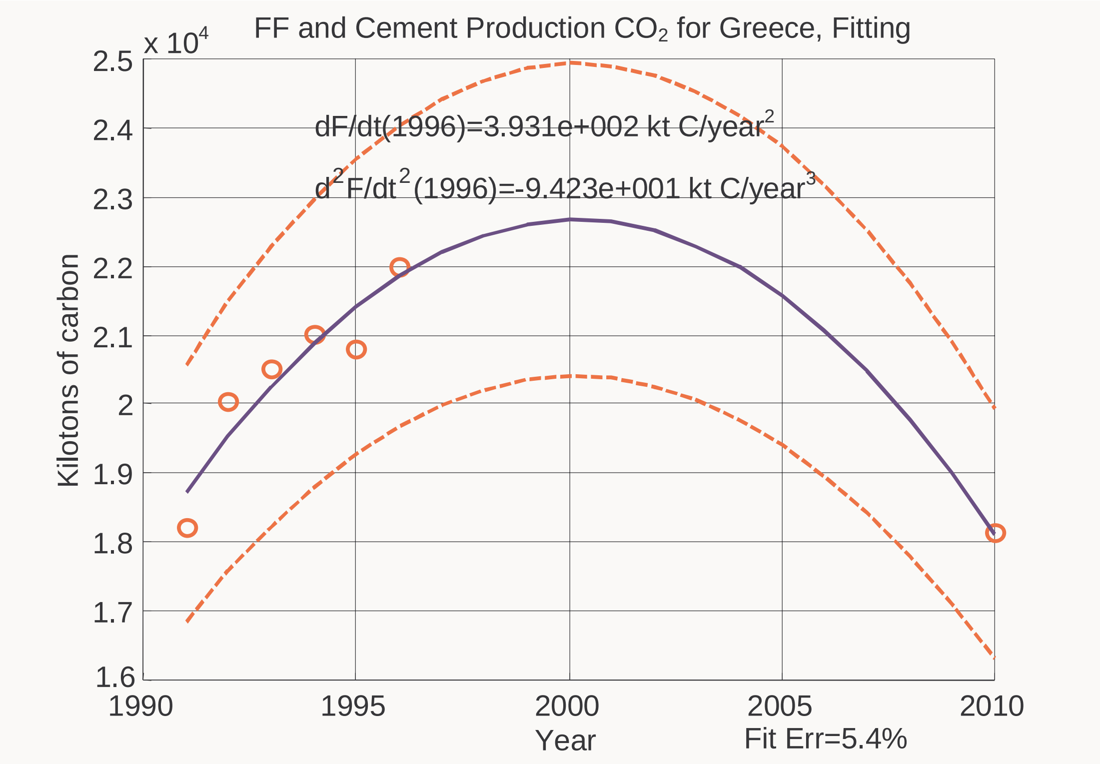


Distribution of absolute values of 1st derivative
number of events
120
100
80
60
40
20
0
0
2
4
6
8
10
12
14
Value, kt C/year2
x 104

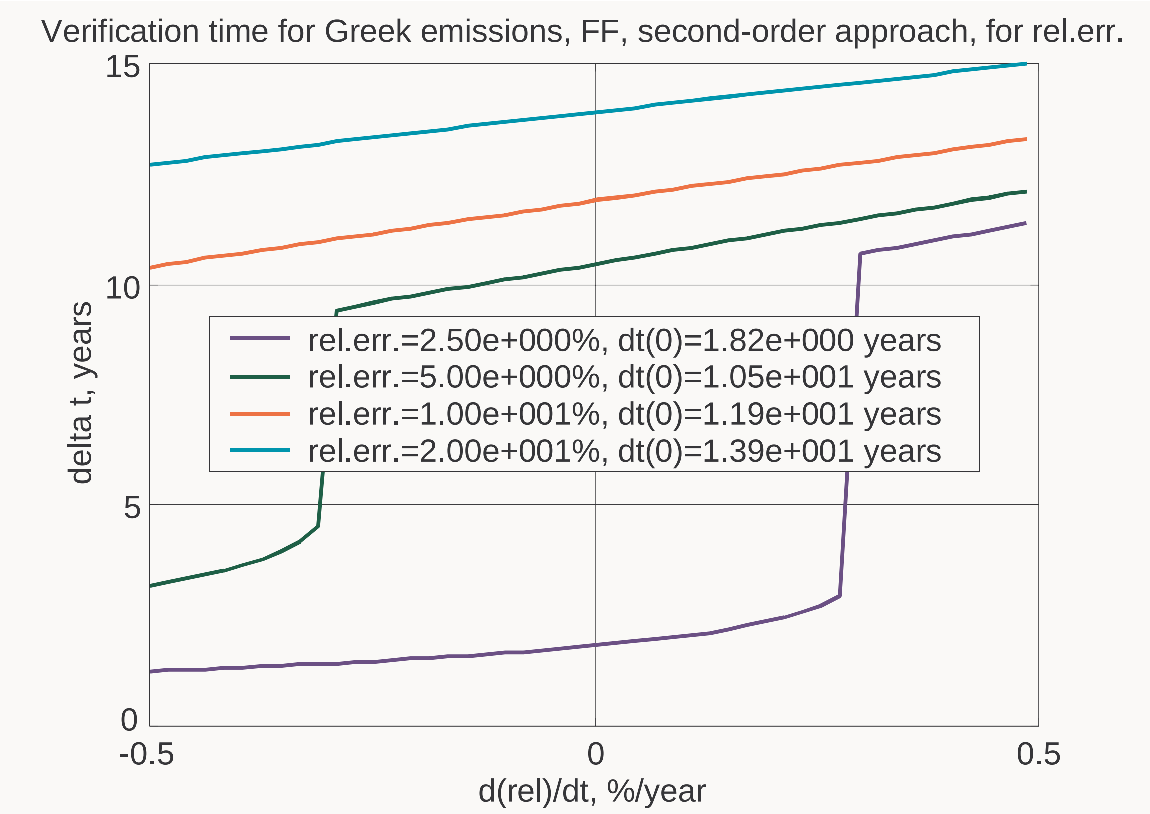


Distribution of absolute values of 2nd derivative
number of events
140
120
100
80
60
40
20
0
0
0.5
1
1.5
2
Value, kt C/year3
x 105

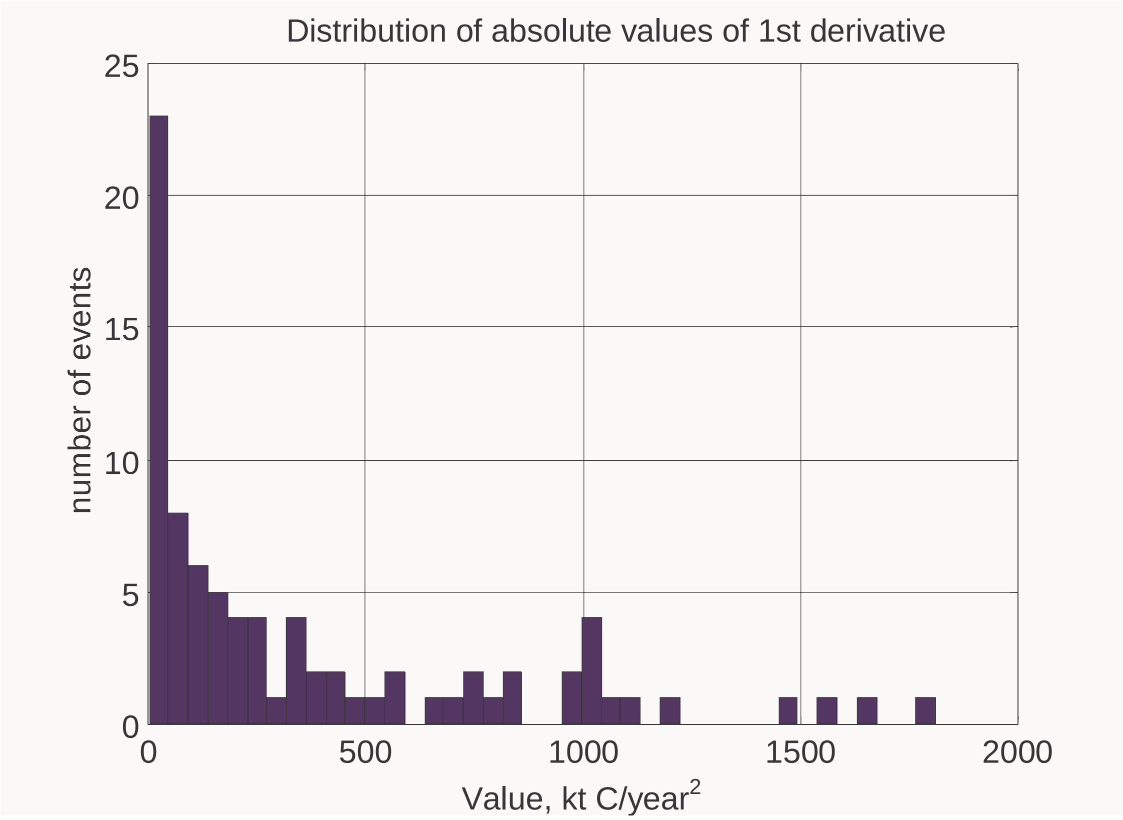
Greece

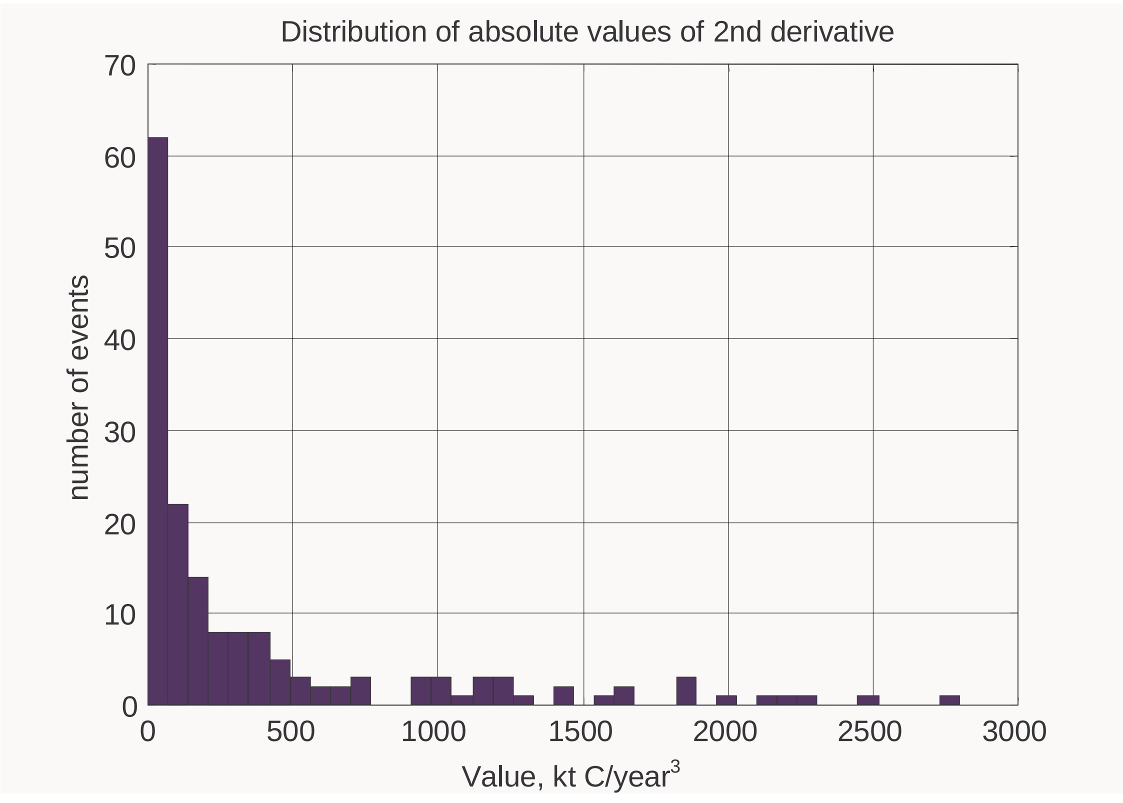


FF and Cement Production CO_2 for Greece, Fitting
x 10^4
2.5
2.4
2.3
2.2
2.1
2
1.9
1.8
1.7
1.6
Kilotons of carbon
dF/dt(1996)=3.931e+002 kt C/year^2
d^2F/dt^2(1996)=-9.423e+001 kt C/year^3
1990
1995
2000
2005
2010
Year
Fit Err=5.4%

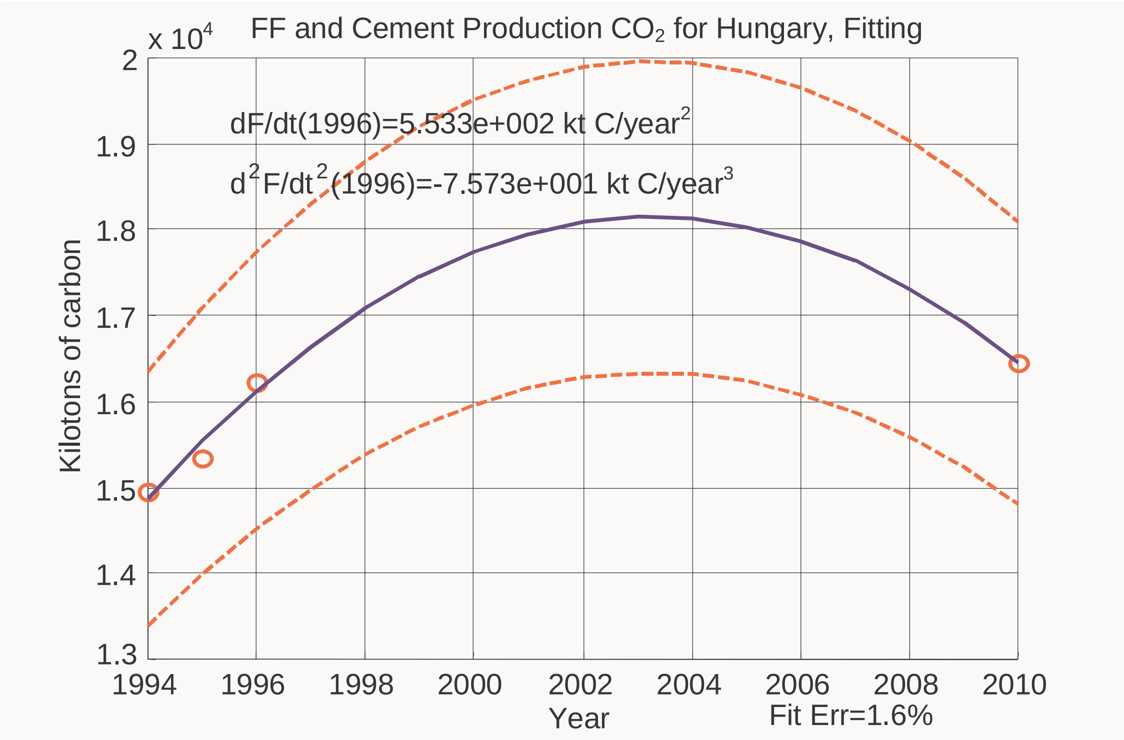


Verification time for Greek emissions, FF, second-order approach, for rel.err.
15
10
5
0
delta t, years
rel.err.=2.50e+000%, dt(0)=1.82e+000 years
rel.err.=5.00e+000%, dt(0)=1.05e+001 years
rel.err.=1.00e+001%, dt(0)=1.19e+001 years
rel.err.=2.00e+001%, dt(0)=1.39e+001 years
-0.5
0
0.5
d(rel)/dt, %/year

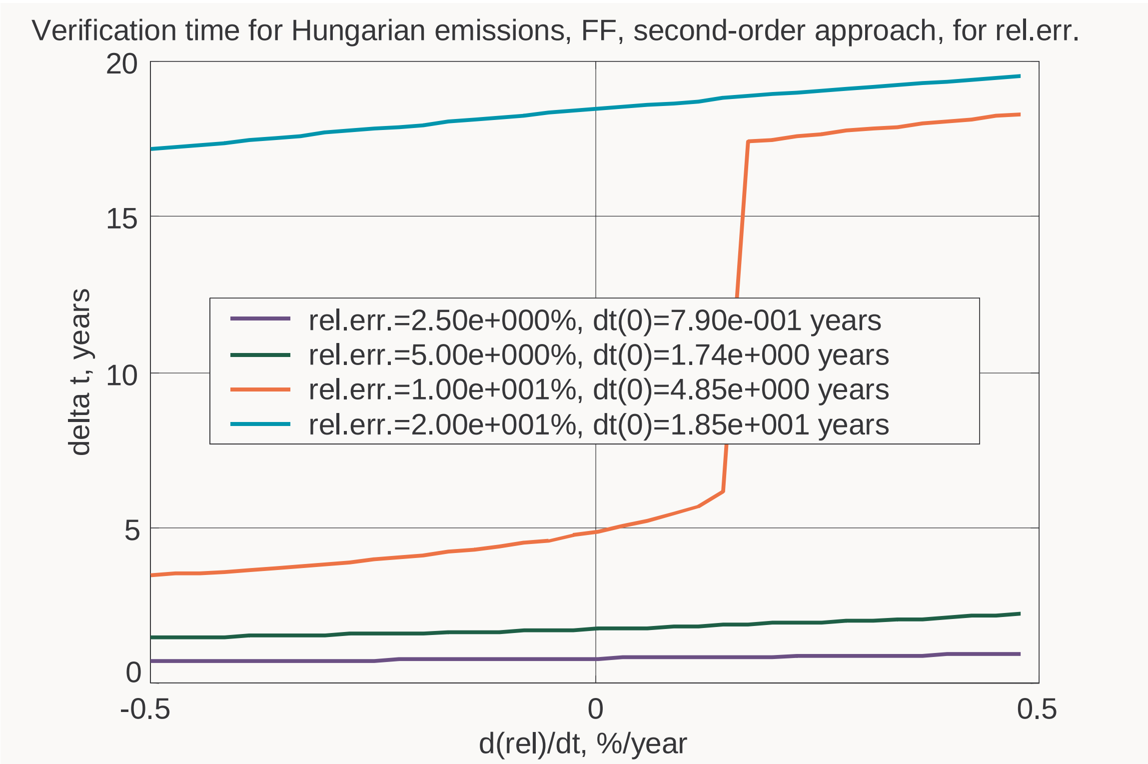

Distribution of absolute values of 1st derivative
number of events
25
20
15
10
5
0
0
500
1000
1500
2000
Value, kt C/year2


Distribution of absolute values of 2nd derivative
number of events
70
60
50
40
30
20
10
0
0
500
1000
1500
2000
2500
3000
Value, kt C/year3

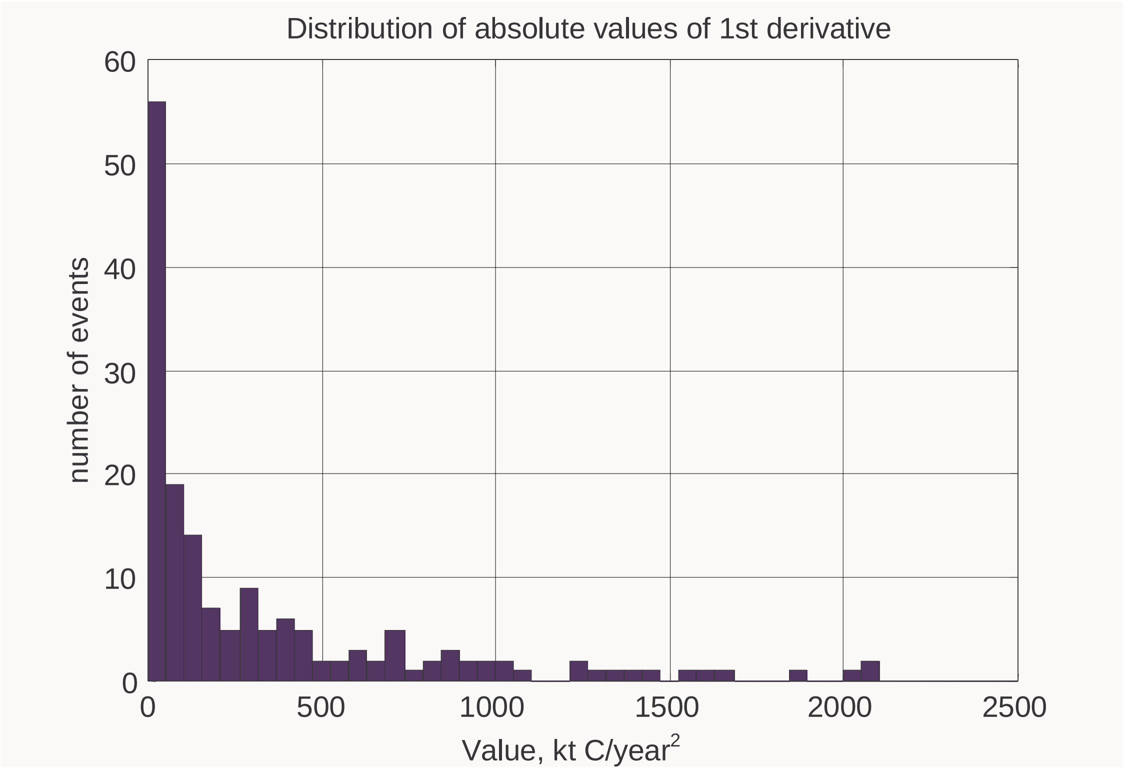
Hungary

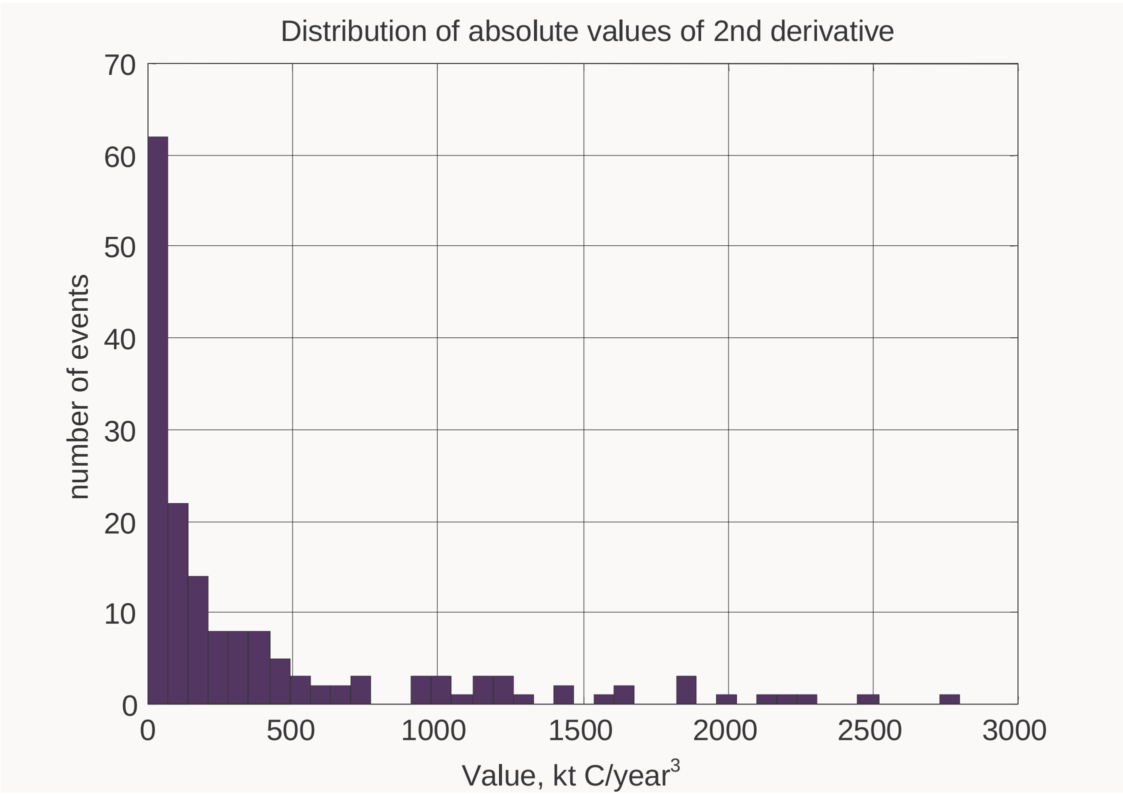


x 10^4
FF and Cement Production CO2 for Hungary, Fitting
dF/dt(1996)=5.533e+002 kt C/year^2
d^2F/dt^2(1996)=-7.573e+001 kt C/year^3
Kilotons of carbon
2
1.9
1.8
1.7
1.6
1.5
1.4
1.3
1994
1996
1998
2000
2002
2004
2006
2008
2010
Year
Fit Err=1.6%

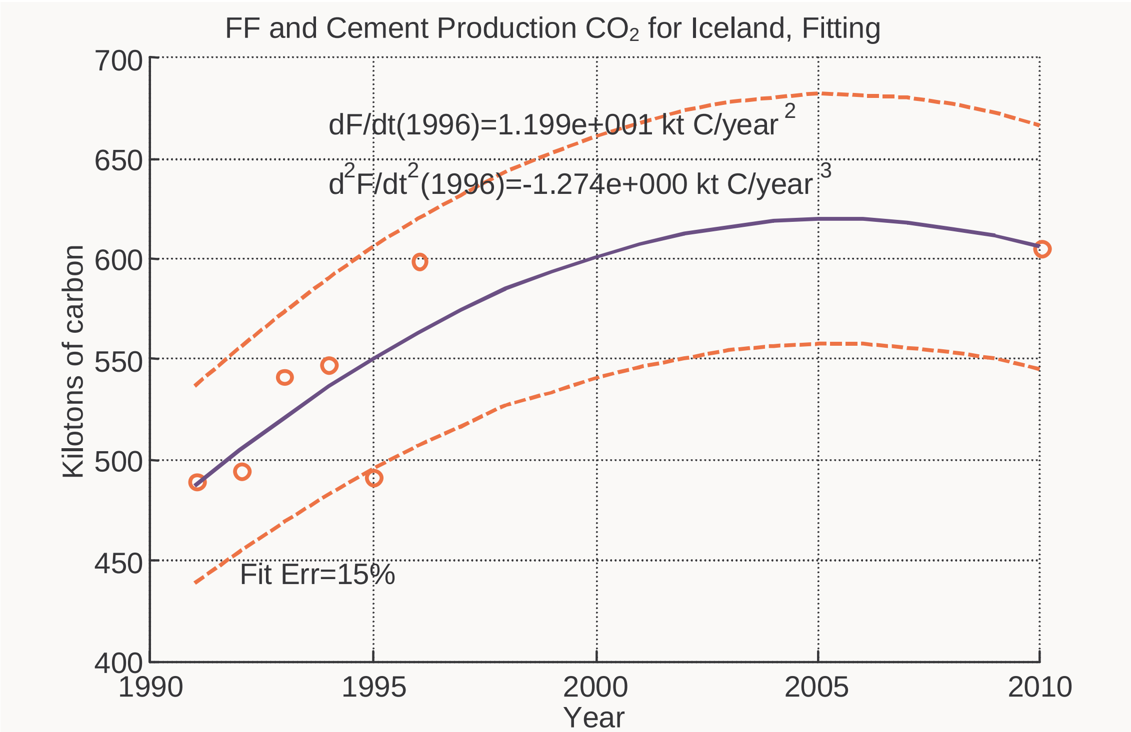


Verification time for Hungarian emissions, FF, second-order approach, for rel.err.
delta t, years
20
15
10
5
0
-0.5
0
0.5
d(rel)/dt, %/year
rel.err.=2.50e+000%, dt(0)=7.90e-001 years
rel.err.=5.00e+000%, dt(0)=1.74e+000 years
rel.err.=1.00e+001%, dt(0)=4.85e+000 years
rel.err.=2.00e+001%, dt(0)=1.85e+001 years

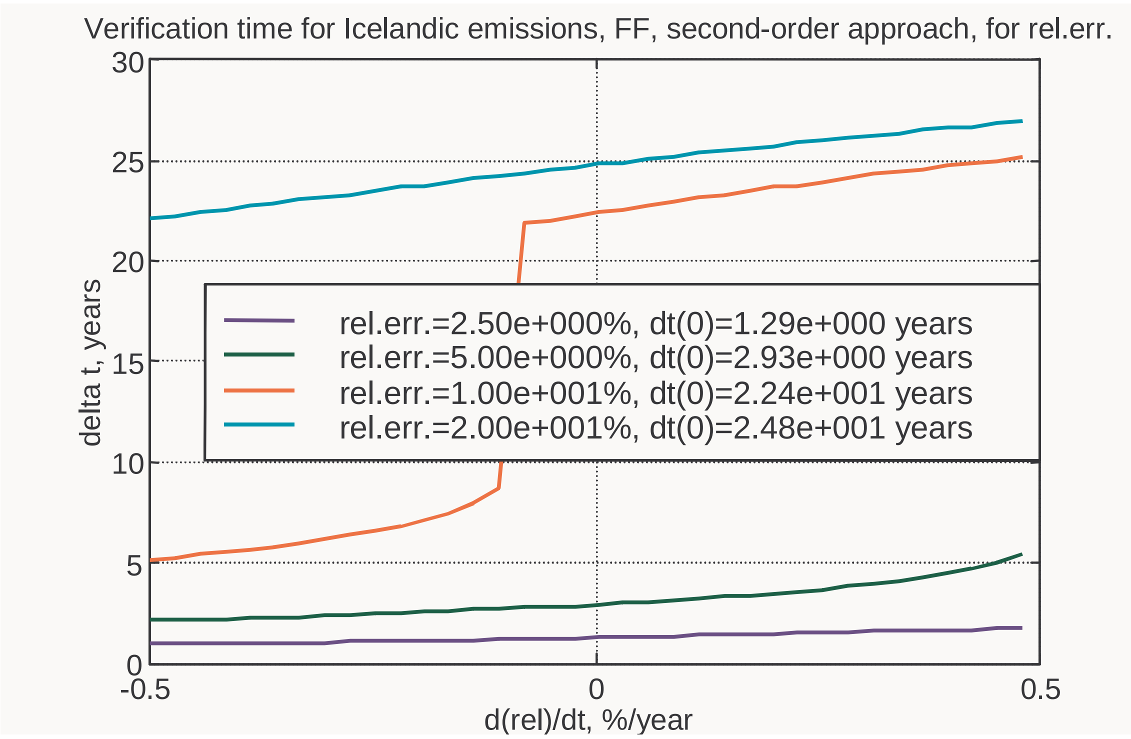

Distribution of absolute values of 1st derivative
number of events
0
10
20
30
40
50
60
0
500
1000
1500
2000
2500
Value, kt C/year2


Distribution of absolute values of 2nd derivative
number of events
0
10
20
30
40
50
60
70
0
500
1000
1500
2000
2500
3000
Value, kt C/year3

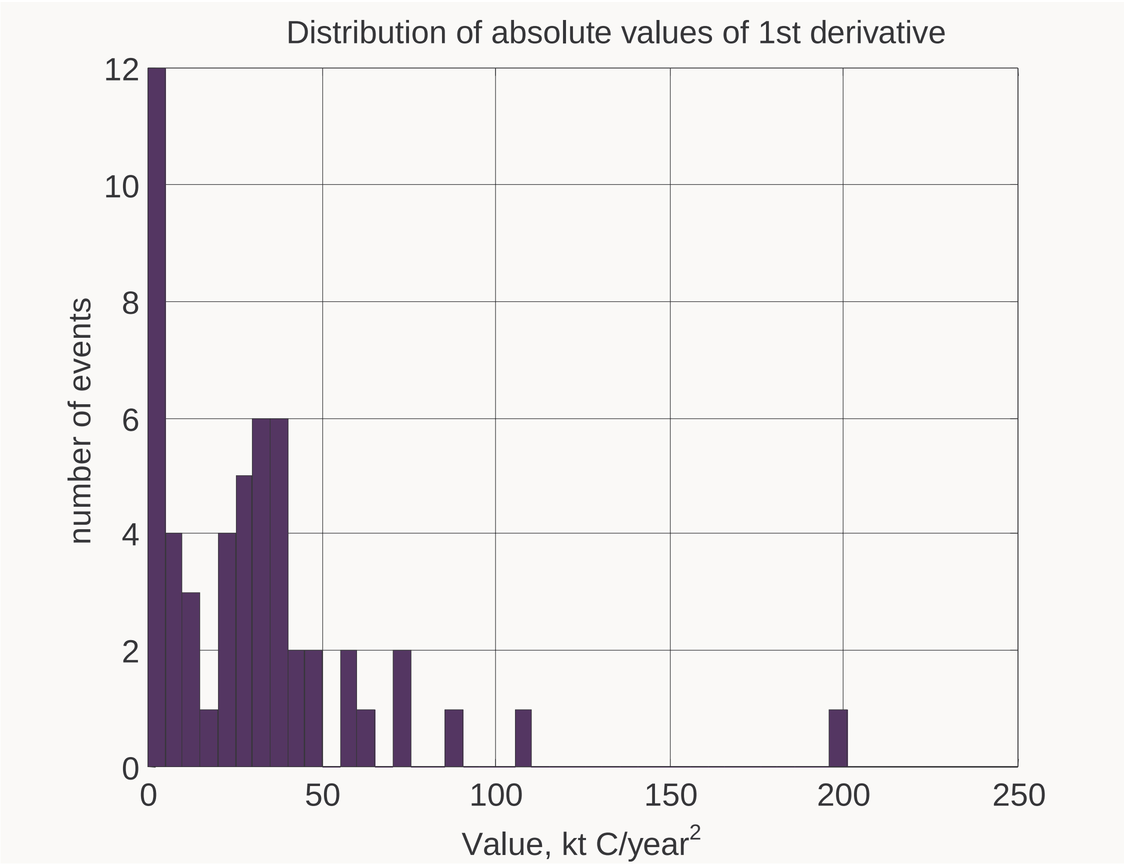
Iceland

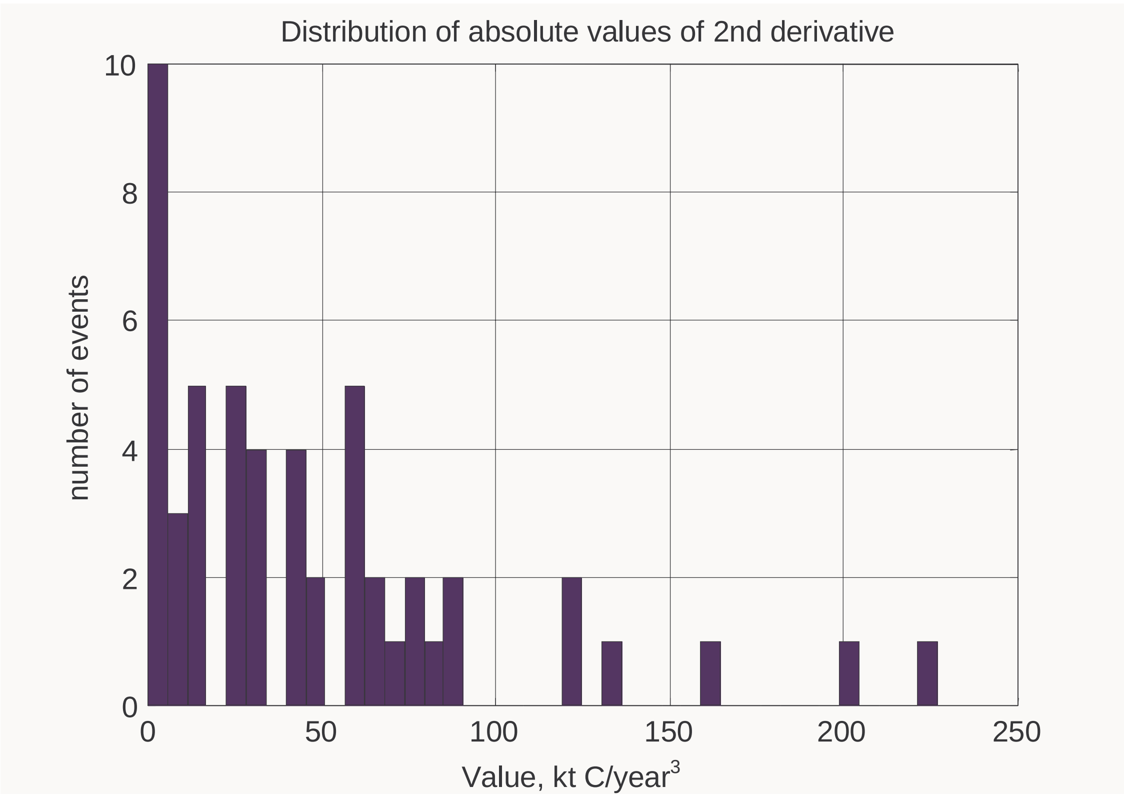


FF and Cement Production CO2 for Iceland, Fitting
dF/dt(1996)=1.199e+001 kt C/year 2
d2F/dt2(1996)=-1.274e+000 kt C/year 3
Fit Err=15%
Kilotons of carbon
700
650
600
550
500
450
400
1990
1995
2000
2005
2010
Year

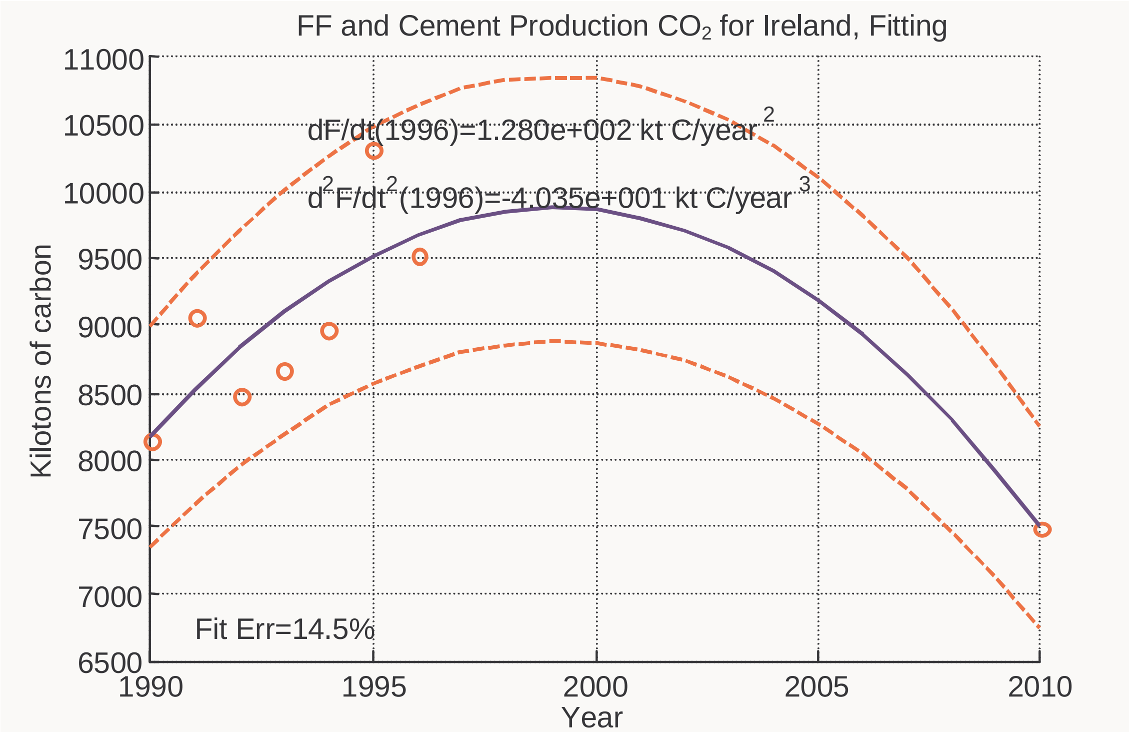


Verification time for Icelandic emissions, FF, second-order approach, for rel.err.
rel.err.=2.50e+000%, dt(0)=1.29e+000 years
rel.err.=5.00e+000%, dt(0)=2.93e+000 years
rel.err.=1.00e+001%, dt(0)=2.24e+001 years
rel.err.=2.00e+001%, dt(0)=2.48e+001 years
delta t, years
30
25
20
15
10
5
0
-0.5
0
0.5
d(rel)/dt, %/year

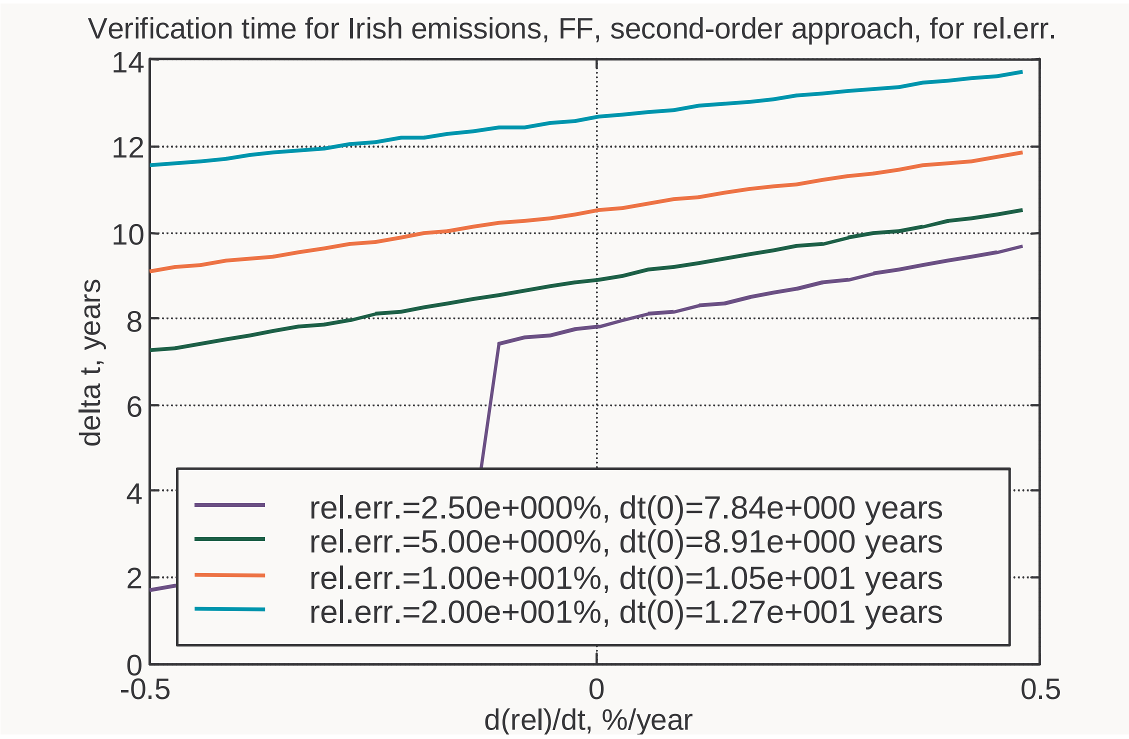

Distribution of absolute values of 1st derivative
number of events
0
2
4
6
8
10
12
0
50
100
150
200
250
Value, kt C/year^2


Distribution of absolute values of 2nd derivative
number of events
0
2
4
6
8
10
0
50
100
150
200
250
Value, kt C/year^3

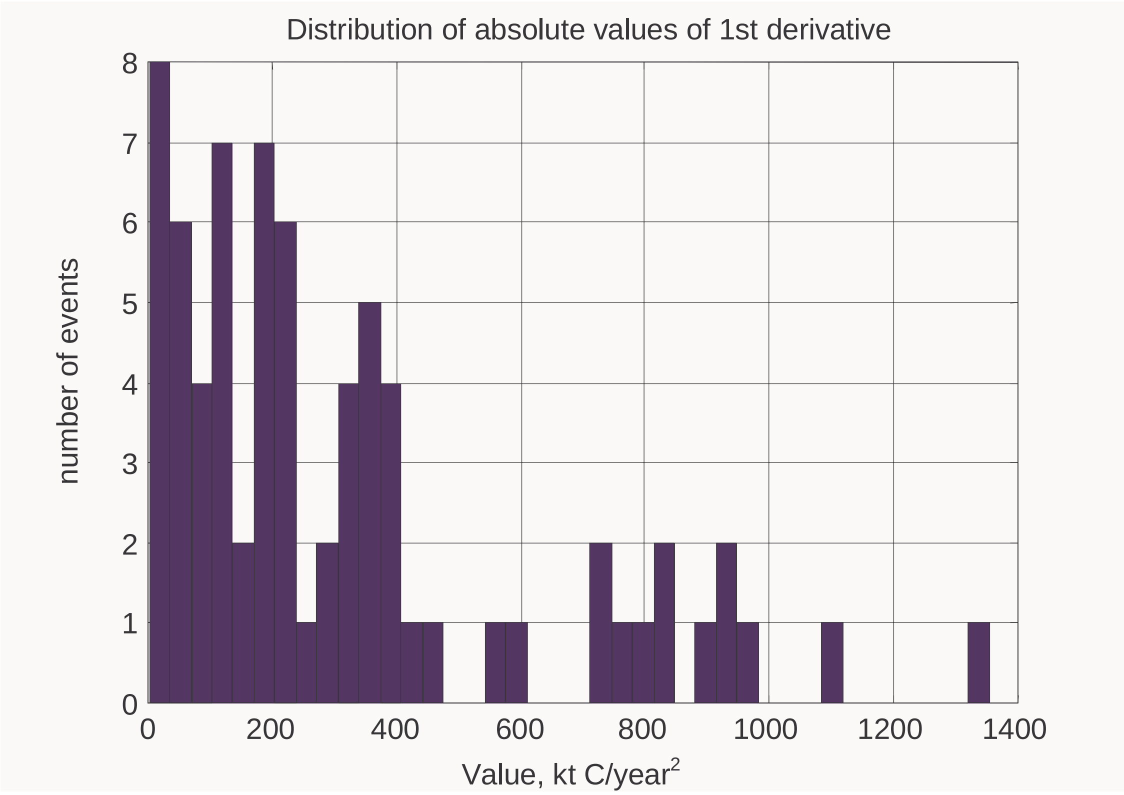
Ireland

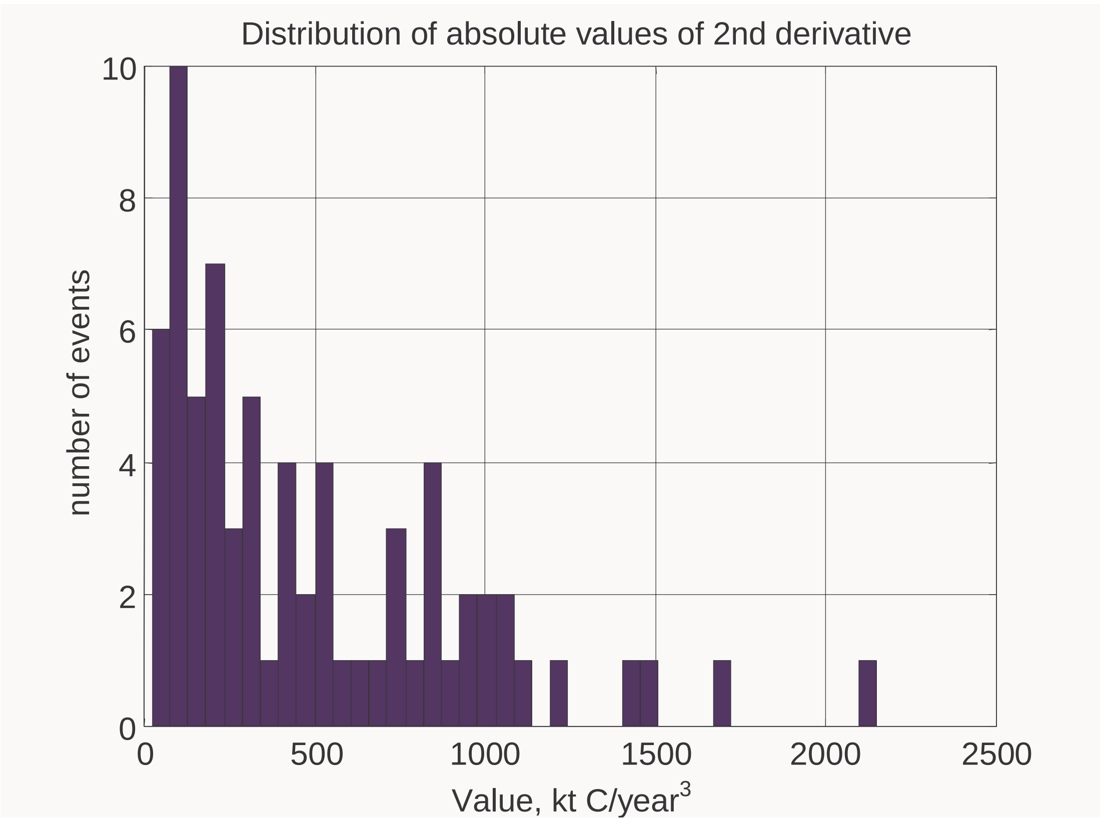


FF and Cement Production CO_2 for Ireland, Fitting
dF/dt(1996)=1.280e+002 kt C/year^2
d^2F/dt^2(1996)=-4.035e+001 kt C/year^3
Fit Err=14.5%
Kilotons of carbon
Year
11000
10500
10000
9500
9000
8500
8000
7500
7000
6500
1990
1995
2000
2005
2010

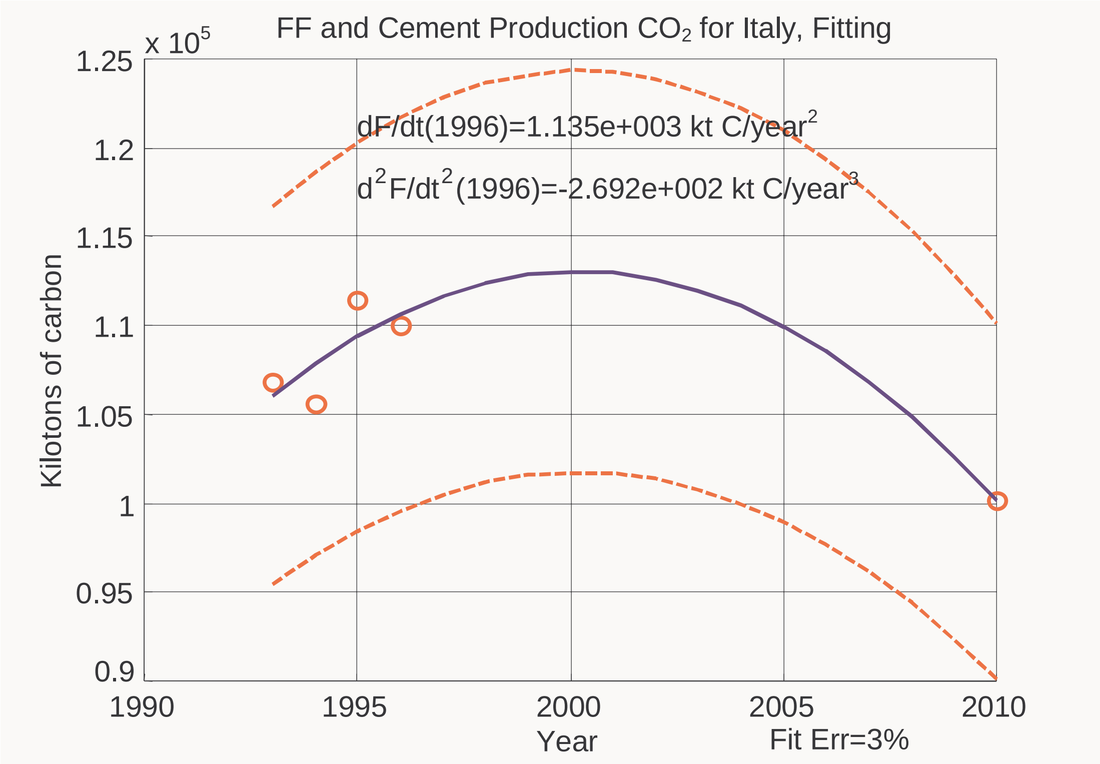


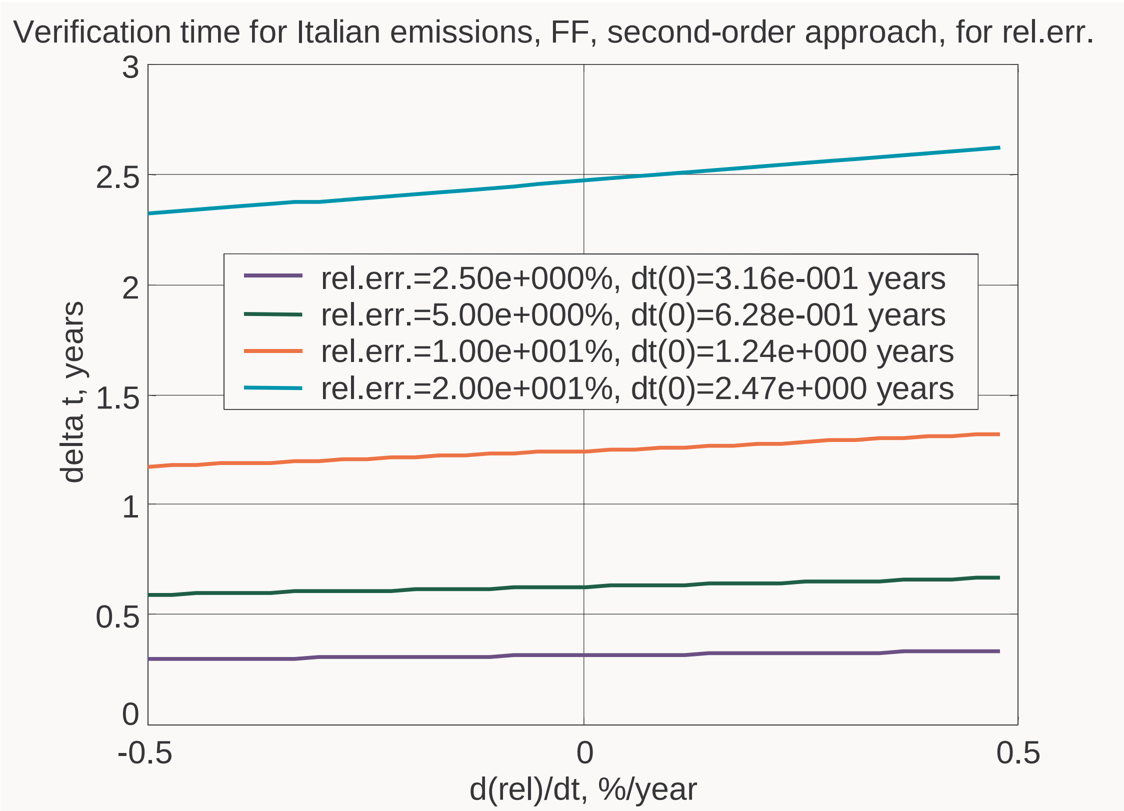
Verification time for Irish emissions, FF, second-order approach, for rel.err.
delta t, years
d(rel)/dt, %/year
rel.err.=2.50e+000%, dt(0)=7.84e+000 years
rel.err.=5.00e+000%, dt(0)=8.91e+000 years
rel.err.=1.00e+001%, dt(0)=1.05e+001 years
rel.err.=2.00e+001%, dt(0)=1.27e+001 years
14
12
10
8
6
4
2
0
-0.5
0
0.5

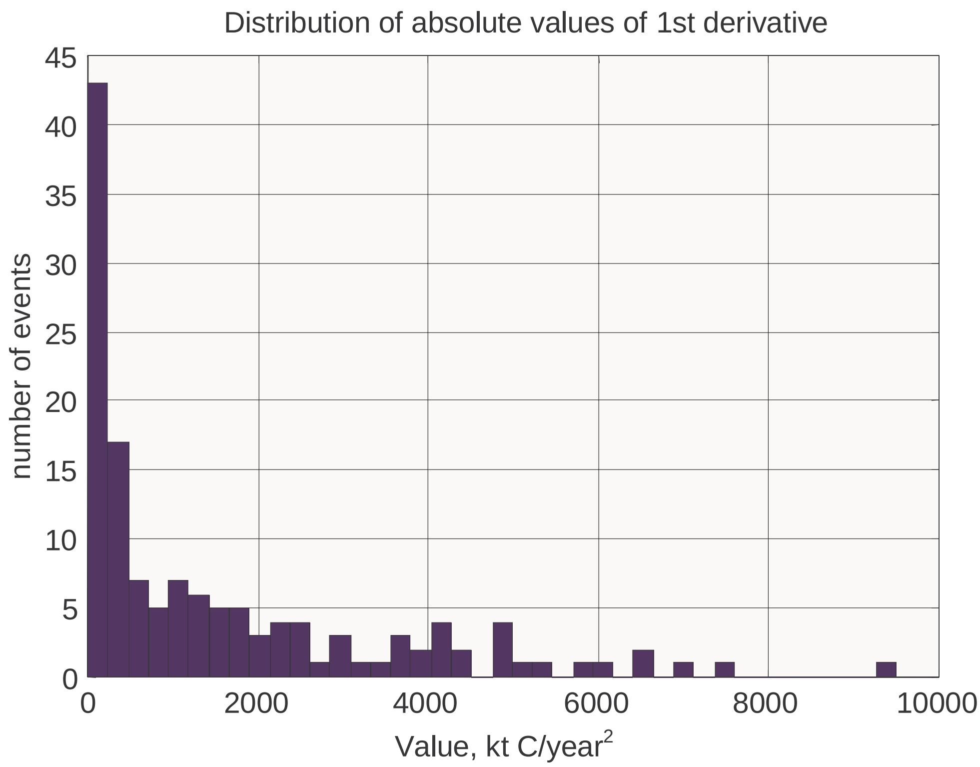

Distribution of absolute values of 1st derivative
number of events
8
7
6
5
4
3
2
1
0
0
200
400
600
800
1000
1200
1400
Value, kt C/year2


Distribution of absolute values of 2nd derivative
number of events
10
8
6
4
2
0
0
500
1000
1500
2000
2500
Value, kt C/year3

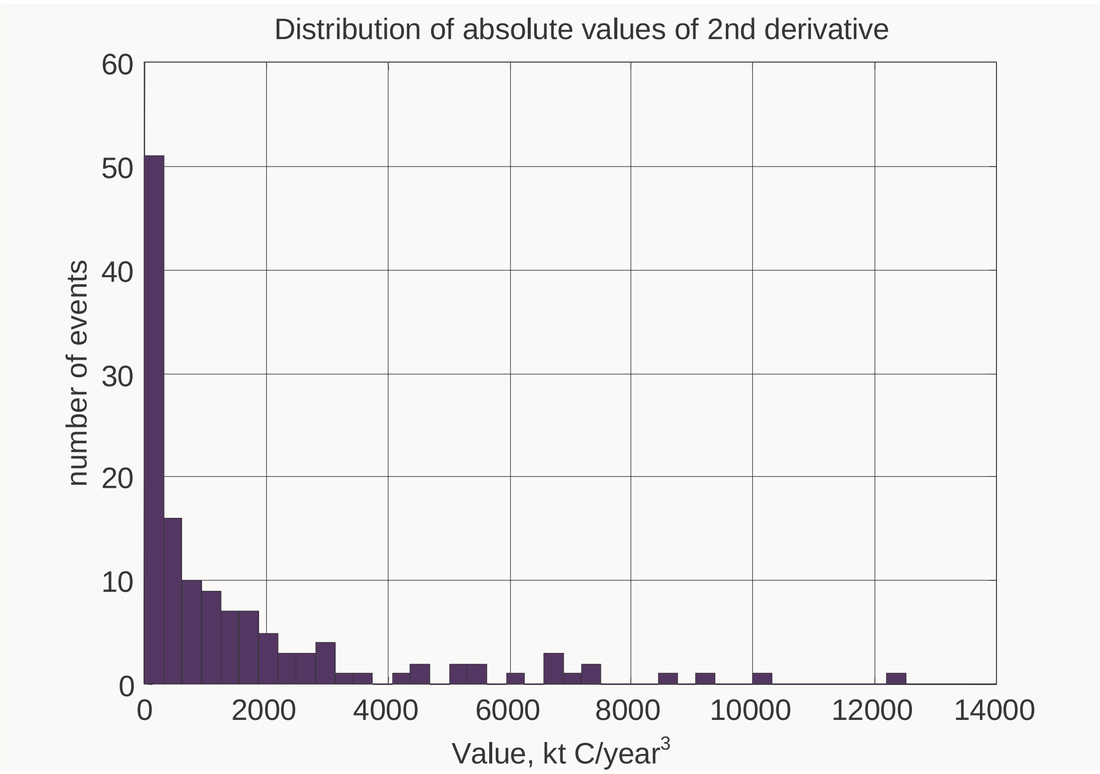
Italy


FF and Cement Production CO2 for Italy, Fitting
x 10^5
1.25
1.2
1.15
1.1
1.05
1
0.95
0.9
Kilotons of carbon
dF/dt(1996)=1.135e+003 kt C/year^2
d^2F/dt^2(1996)=-2.692e+002 kt C/year^3
1990
1995
2000
2005
2010
Year
Fit Err=3%


Verification time for Italian emissions, FF, second-order approach, for rel.err.
3
2.5
2
1.5
1
0.5
0
delta t, years
rel.err.=2.50e+000%, dt(0)=3.16e-001 years
rel.err.=5.00e+000%, dt(0)=6.28e-001 years
rel.err.=1.00e+001%, dt(0)=1.24e+000 years
rel.err.=2.00e+001%, dt(0)=2.47e+000 years
-0.5
0
0.5
d(rel)/dt, %/year

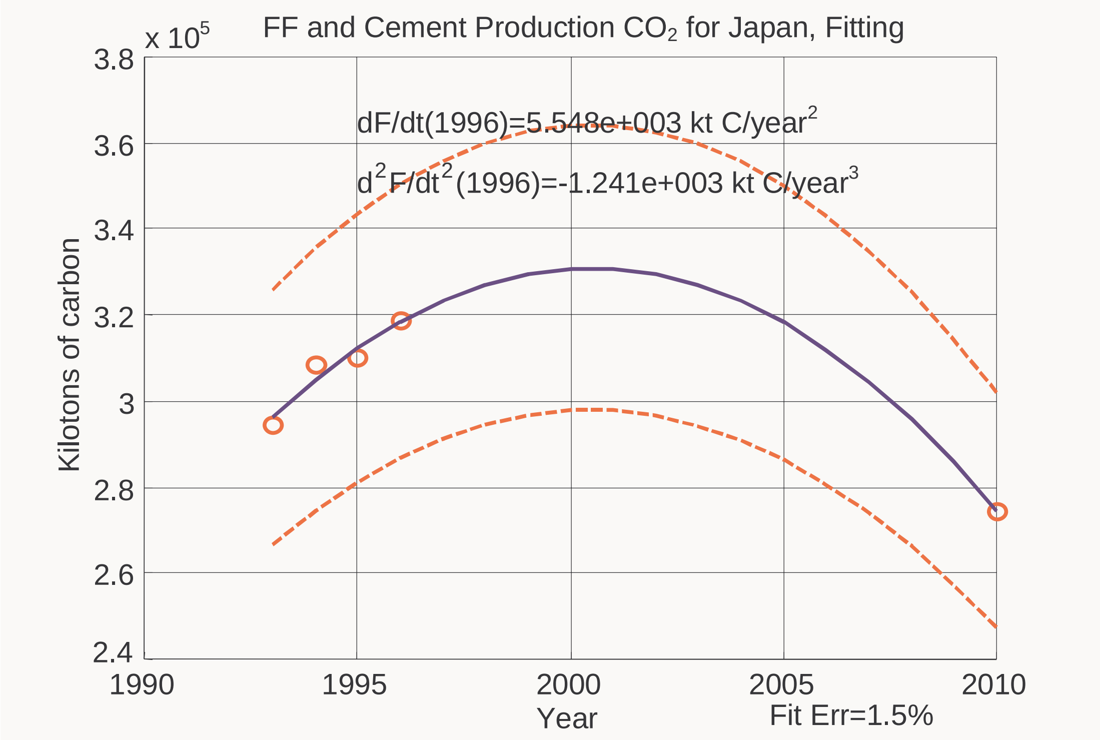


Distribution of absolute values of 1st derivative
number of events
Value, kt C/year^2

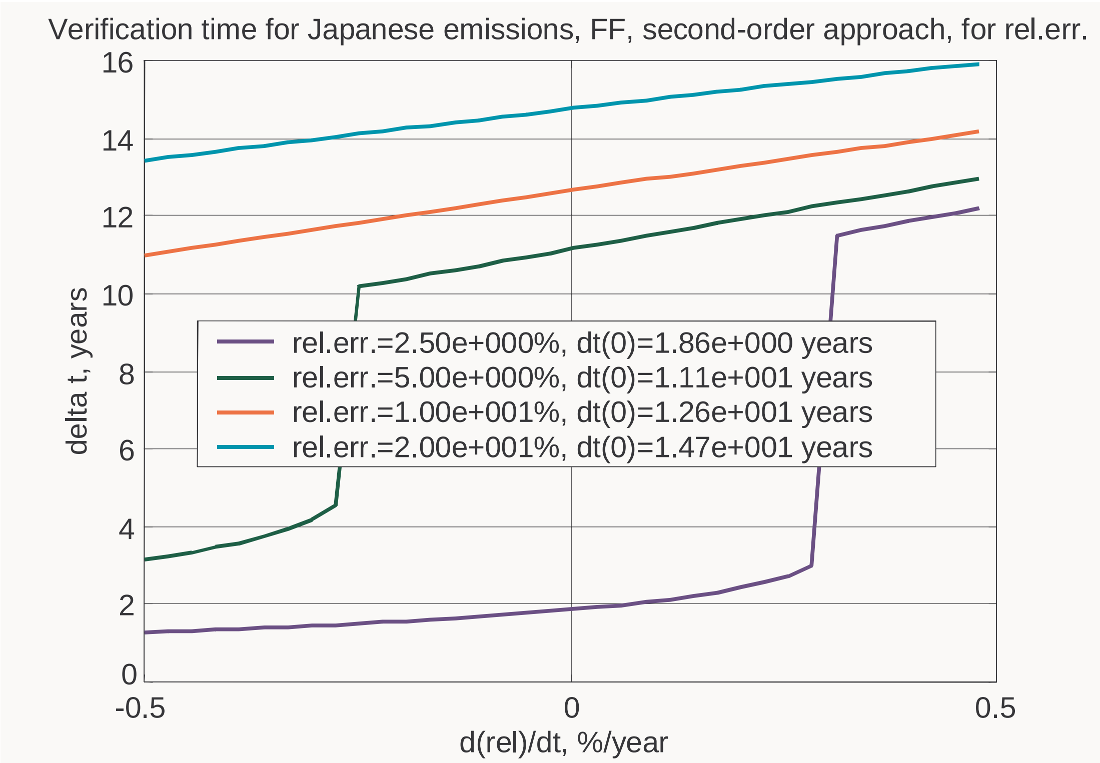


Distribution of absolute values of 2nd derivative
number of events
Value, kt C/year^3

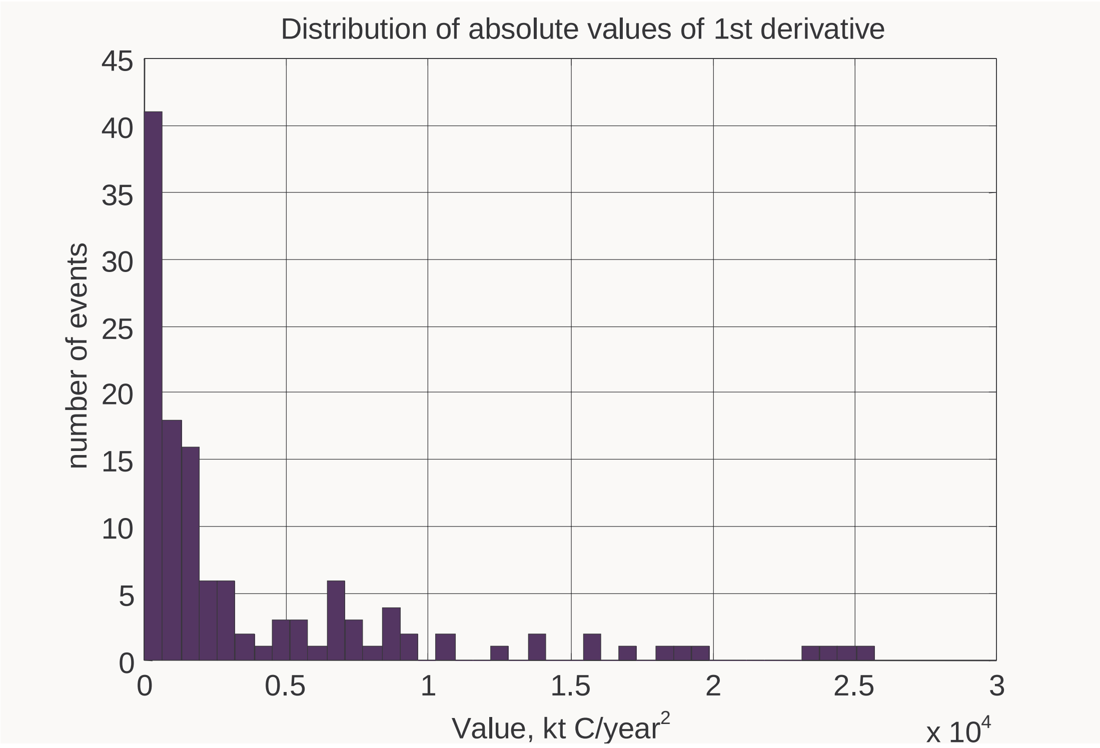
Japan

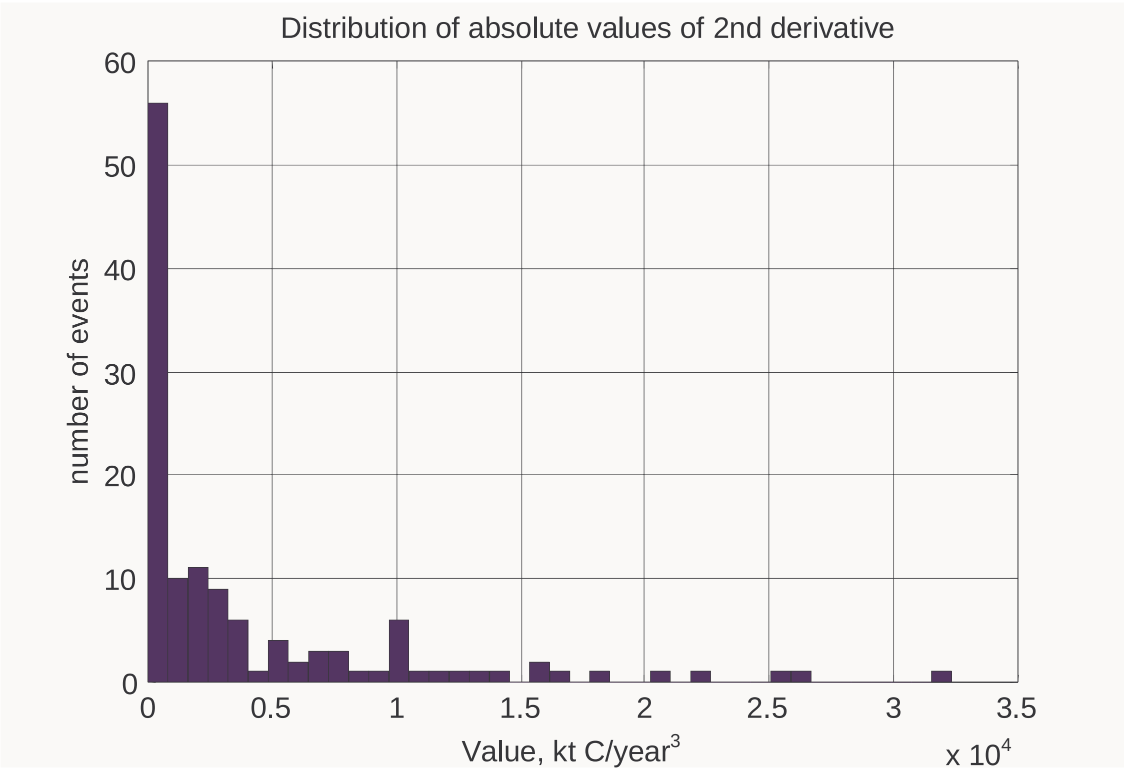


FF and Cement Production CO_2 for Japan, Fitting
x 10^5
3.8
3.6
3.4
3.2
3
2.8
2.6
2.4
Kilotons of carbon
dF/dt(1996)=5.548e+003 kt C/year^2
d^2F/dt^2(1996)=-1.241e+003 kt C/year^3
1990
1995
2000
2005
2010
Year
Fit Err=1.5%

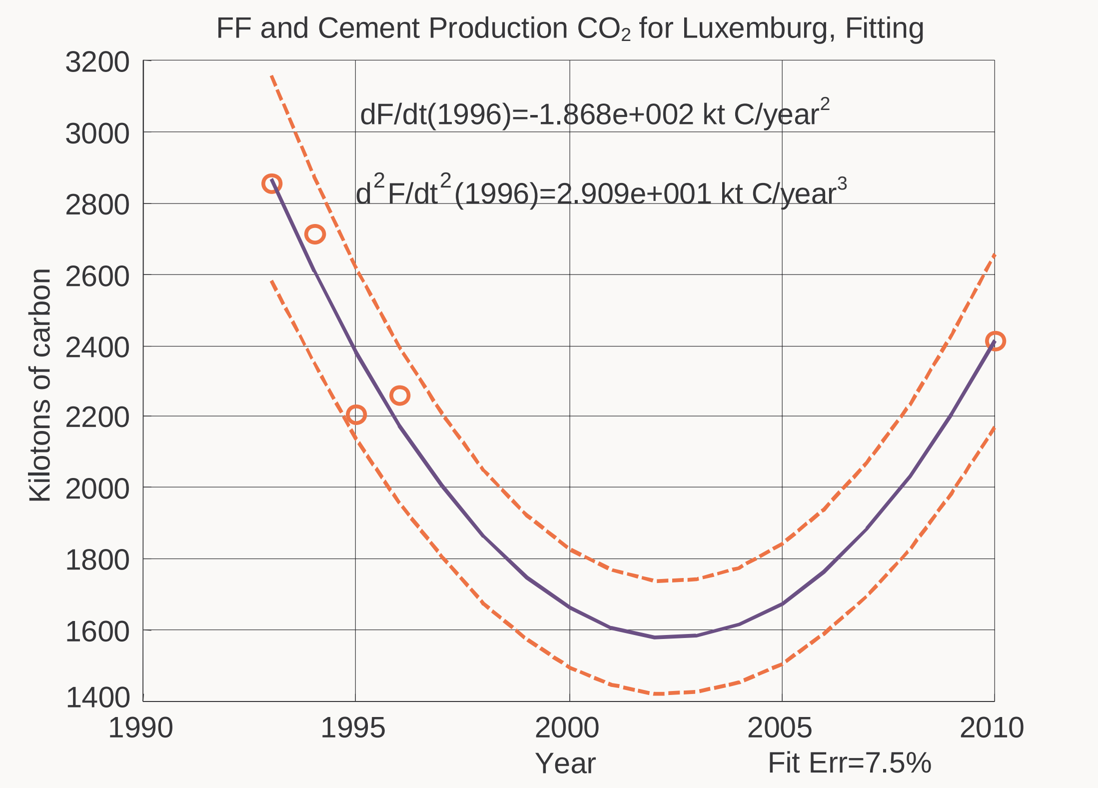


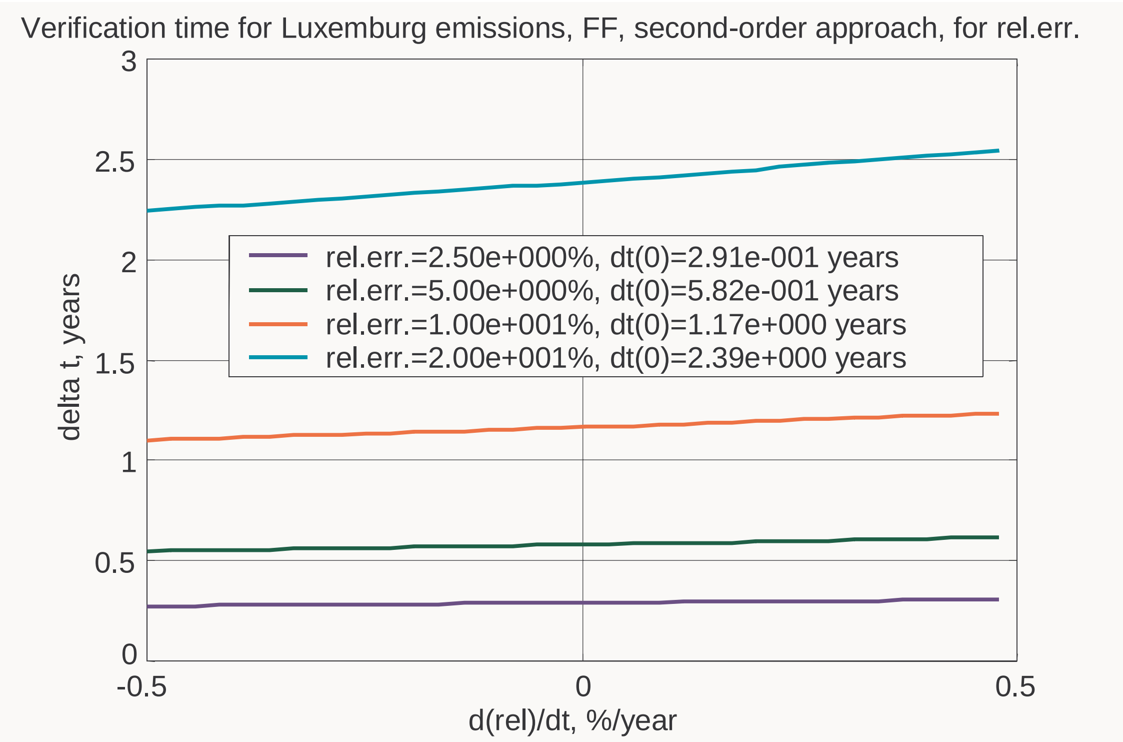
Verification time for Japanese emissions, FF, second-order approach, for rel.err.
16
14
12
10
8
6
4
2
0
delta t, years
rel.err.=2.50e+000%, dt(0)=1.86e+000 years
rel.err.=5.00e+000%, dt(0)=1.11e+001 years
rel.err.=1.00e+001%, dt(0)=1.26e+001 years
rel.err.=2.00e+001%, dt(0)=1.47e+001 years
-0.5
0
0.5
d(rel)/dt, %/year

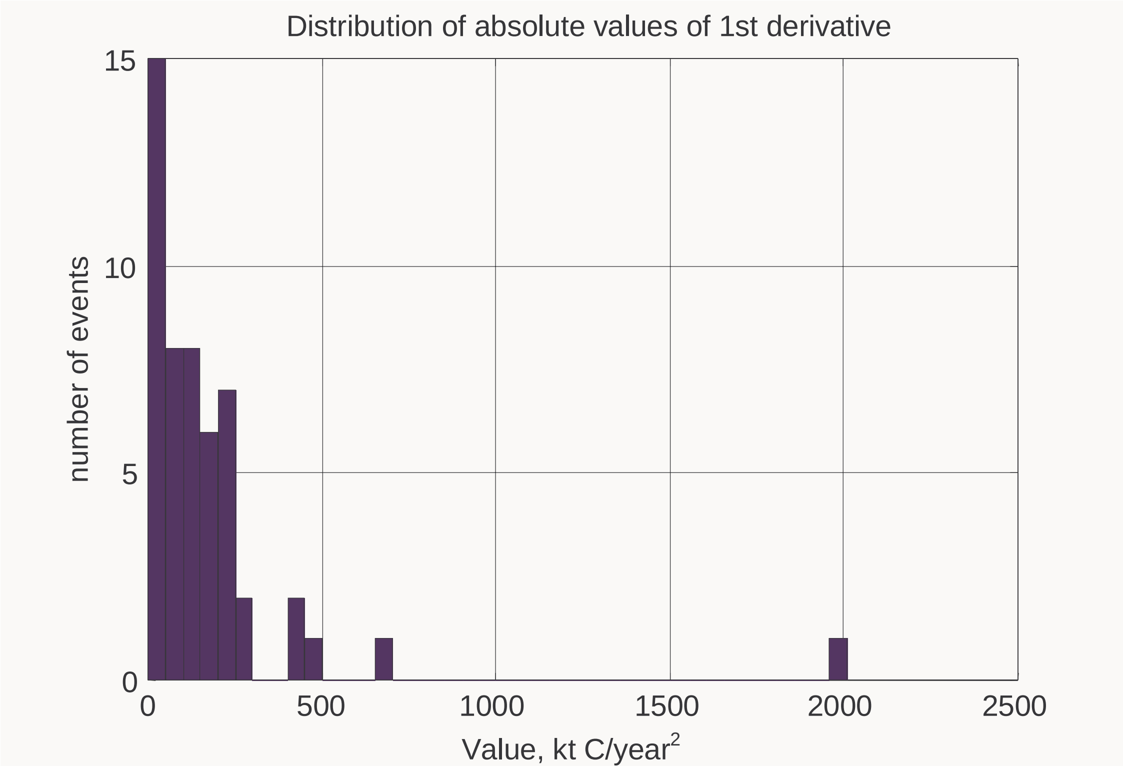

Distribution of absolute values of 1st derivative
number of events
0
5
10
15
20
25
30
35
40
45
0
0.5
1
1.5
2
2.5
3
Value, kt C/year^2
x 10^4

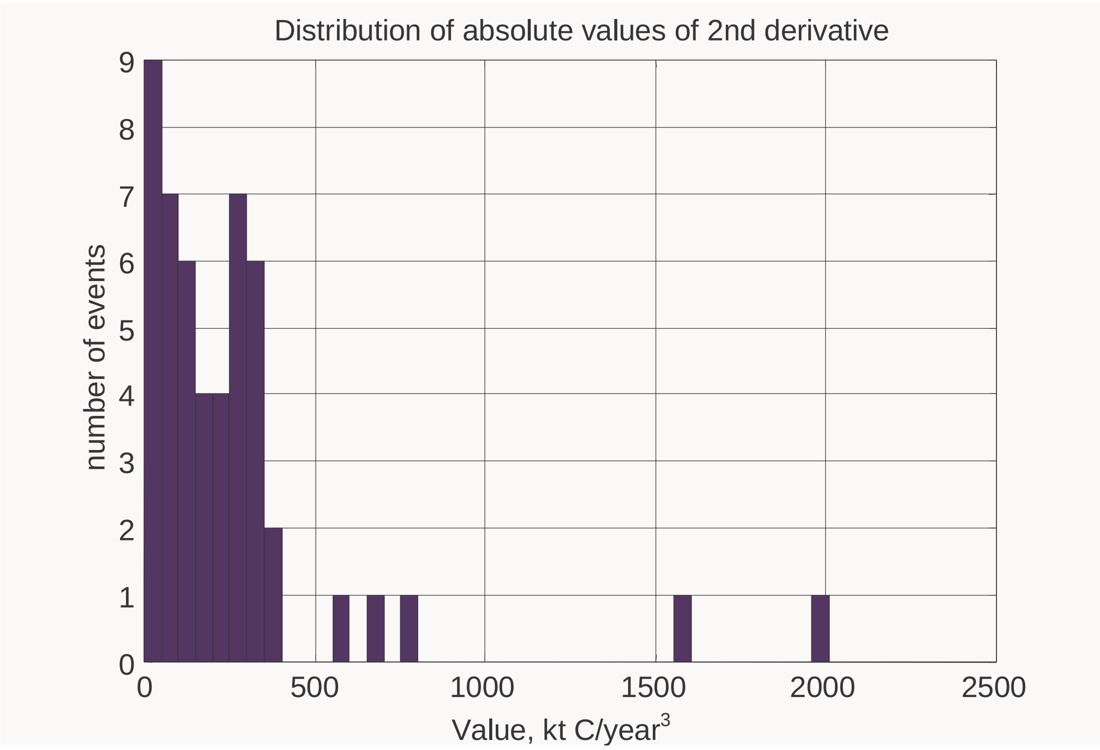

Distribution of absolute values of 2nd derivative
number of events
0
10
20
30
40
50
60
0
0.5
1
1.5
2
2.5
3
3.5
Value, kt C/year^3
x 10^4

Luxemburg

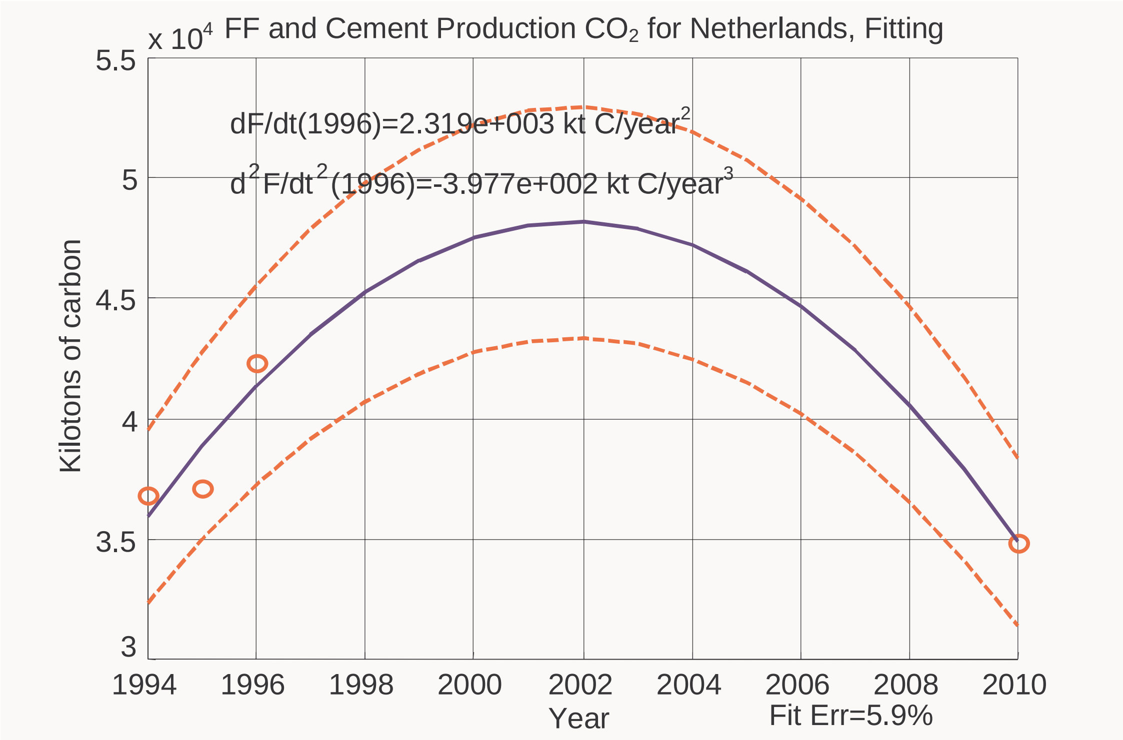

FF and Cement Production CO2 for Luxemburg, Fitting
dF/dt(1996)=-1.868e+002 kt C/year2
d2F/dt2(1996)=2.909e+001 kt C/year3
Kilotons of carbon
3200
3000
2800
2600
2400
2200
2000
1800
1600
1400
1990
1995
2000
2005
2010
Year
Fit Err=7.5%

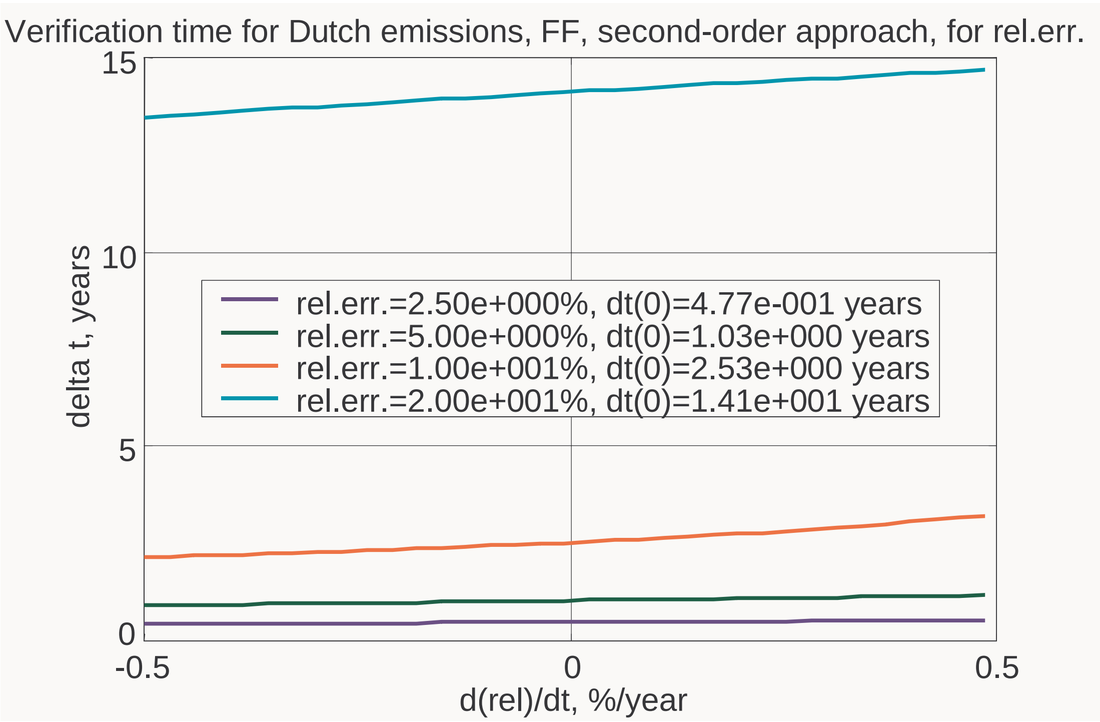

Verification time for Luxemburg emissions, FF, second-order approach, for rel.err.
rel.err.=2.50e+000%, dt(0)=2.91e-001 years
rel.err.=5.00e+000%, dt(0)=5.82e-001 years
rel.err.=1.00e+001%, dt(0)=1.17e+000 years
rel.err.=2.00e+001%, dt(0)=2.39e+000 years
delta t, years
3
2.5
2
1.5
1
0.5
0
-0.5
0
0.5
d(rel)/dt, %/year

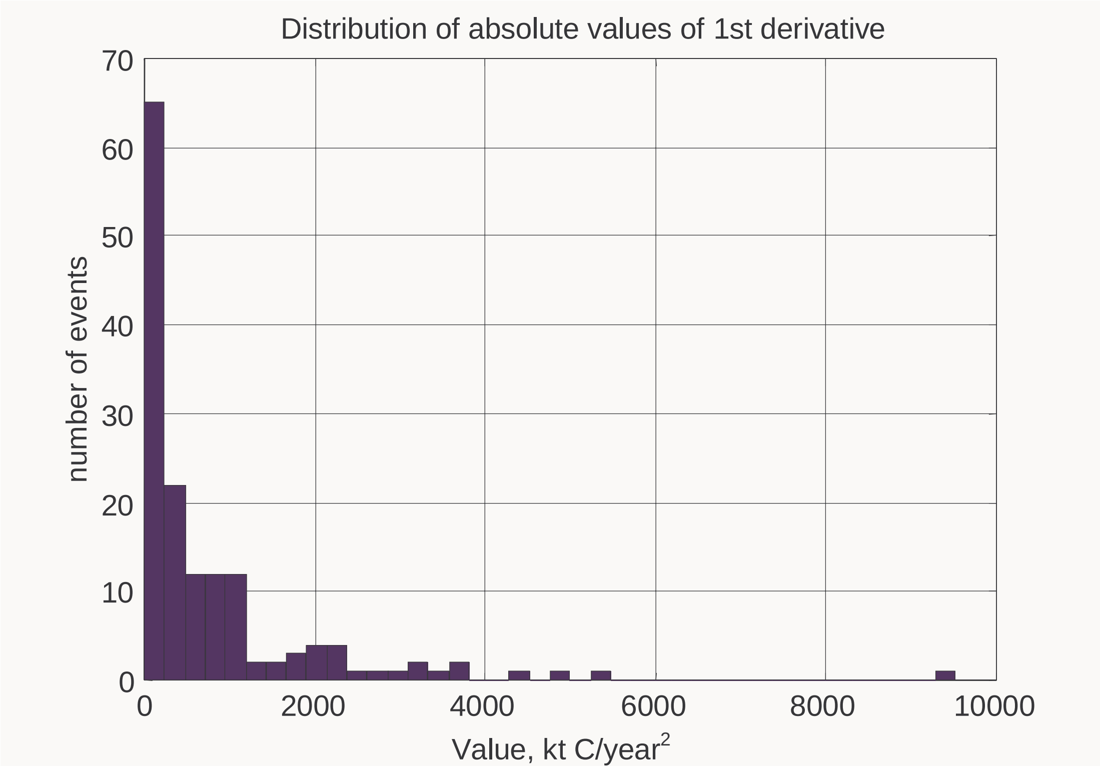

Distribution of absolute values of 1st derivative
number of events
0
5
10
15
0
500
1000
1500
2000
2500
Value, kt C/year2

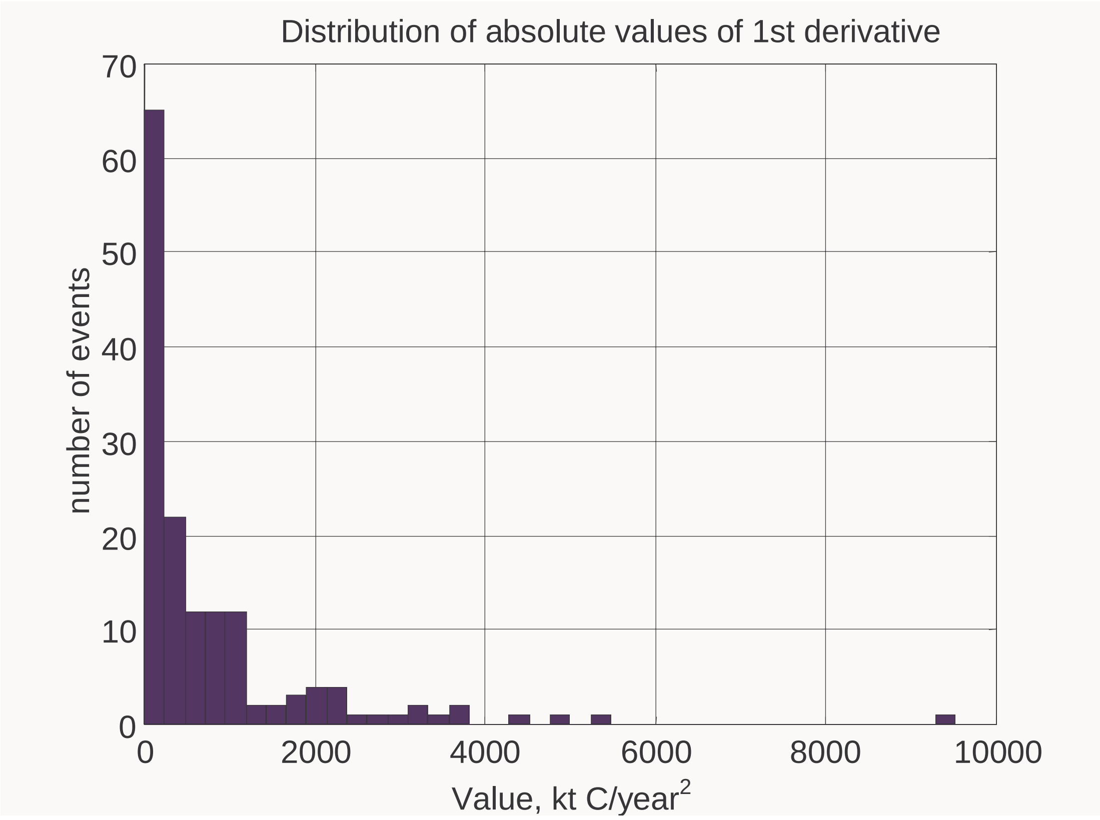

Distribution of absolute values of 2nd derivative
number of events
0
1
2
3
4
5
6
7
8
9
0
500
1000
1500
2000
2500
Value, kt C/year3

Netherlands

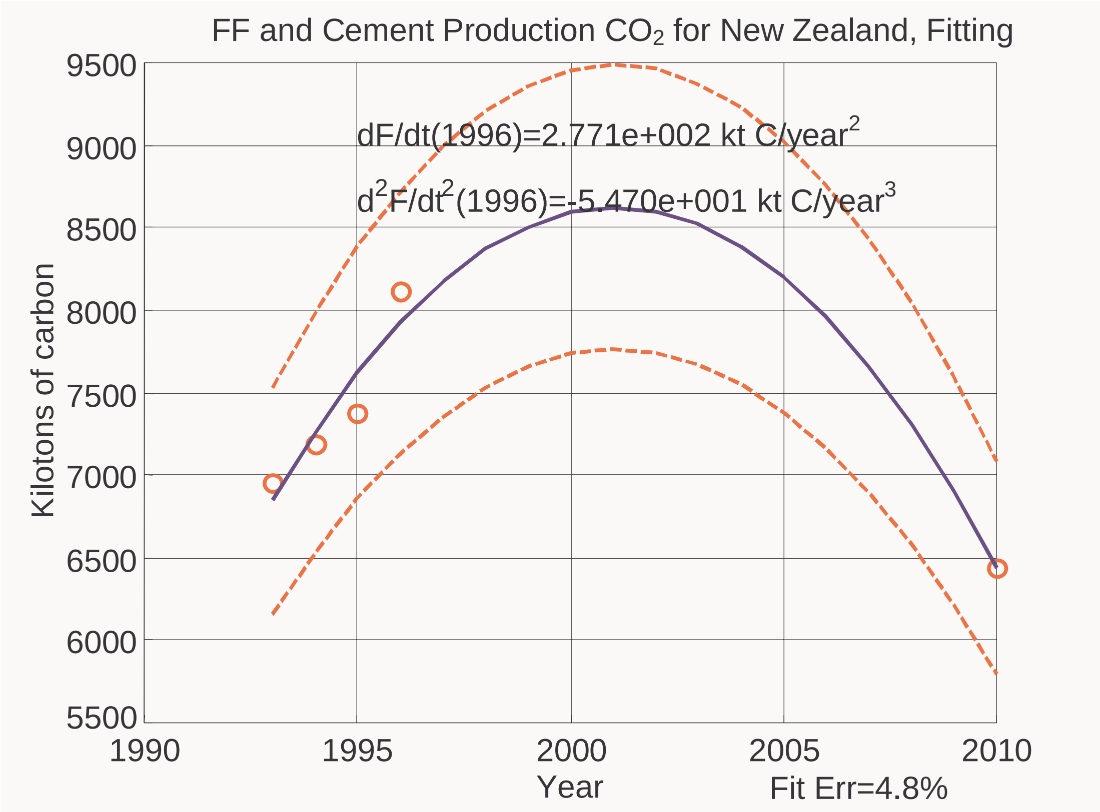




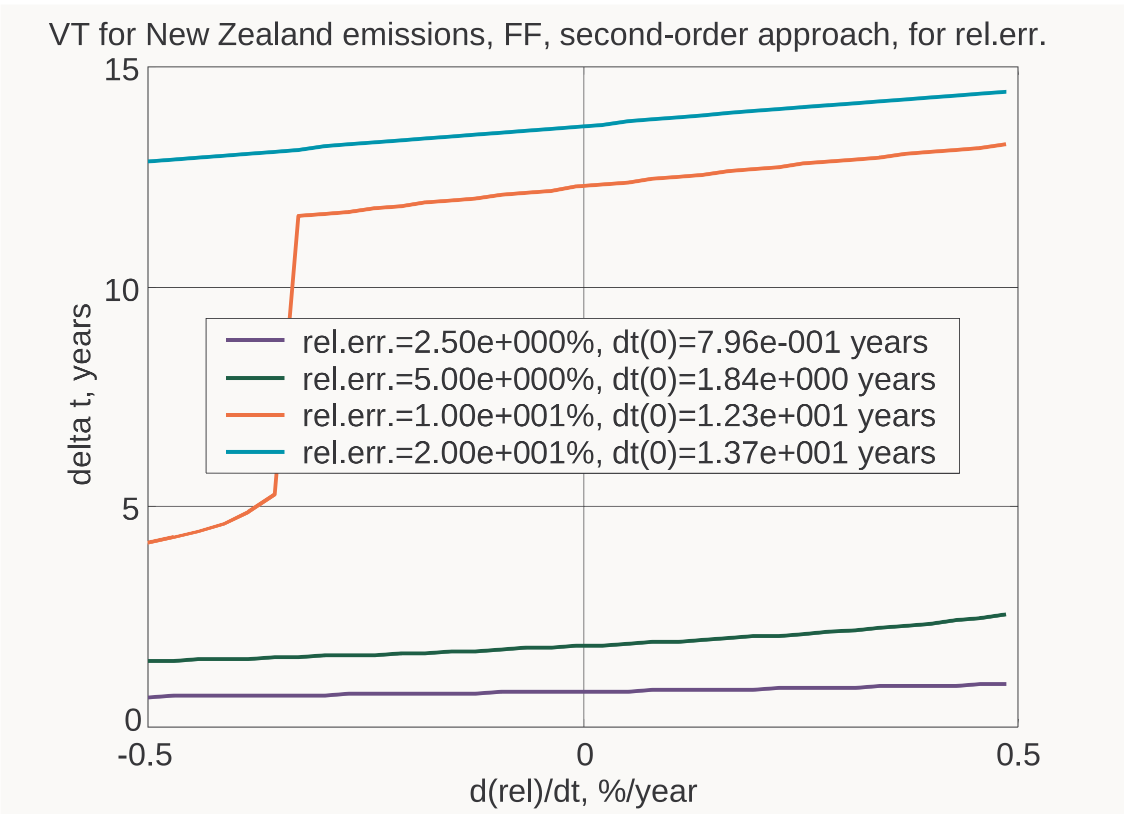

Distribution of absolute values of 1st derivative
number of events
70
60
50
40
30
20
10
0
0
2000
4000
6000
8000
10000
Value, kt C/year^2


Distribution of absolute values of 1st derivative
number of events
70
60
50
40
30
20
10
0
0
2000
4000
6000
8000
10000
Value, kt C/year^2

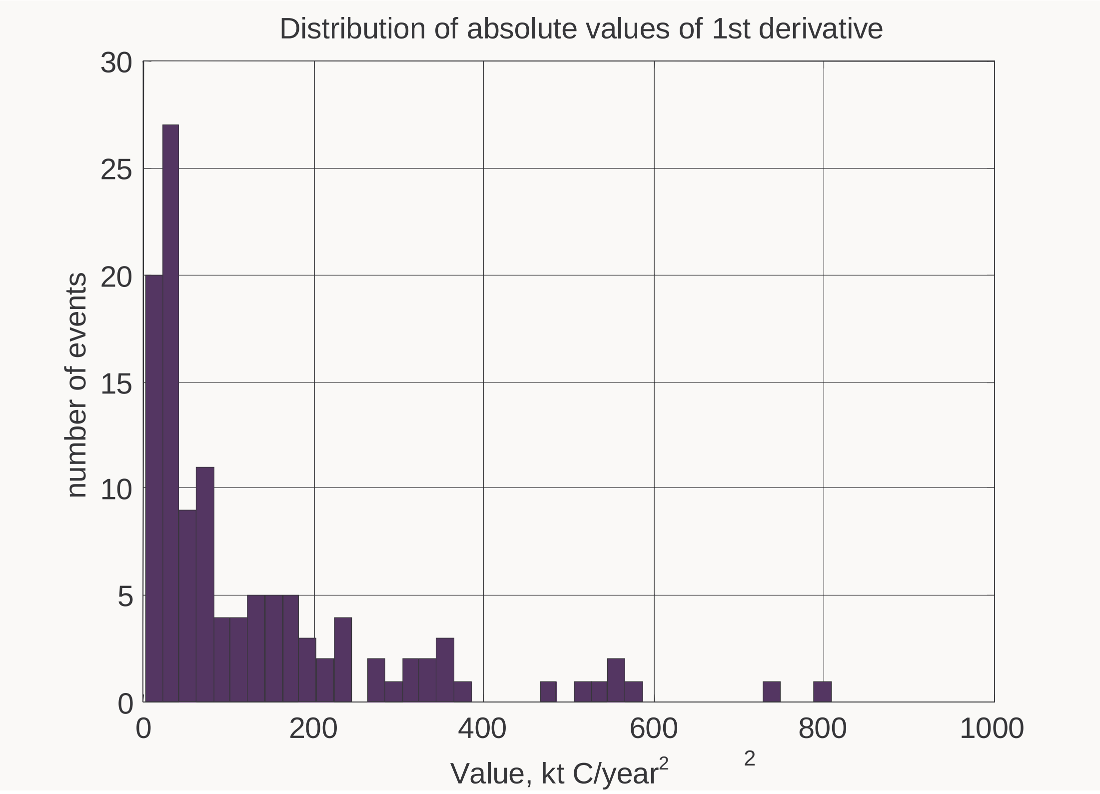
New Zealand

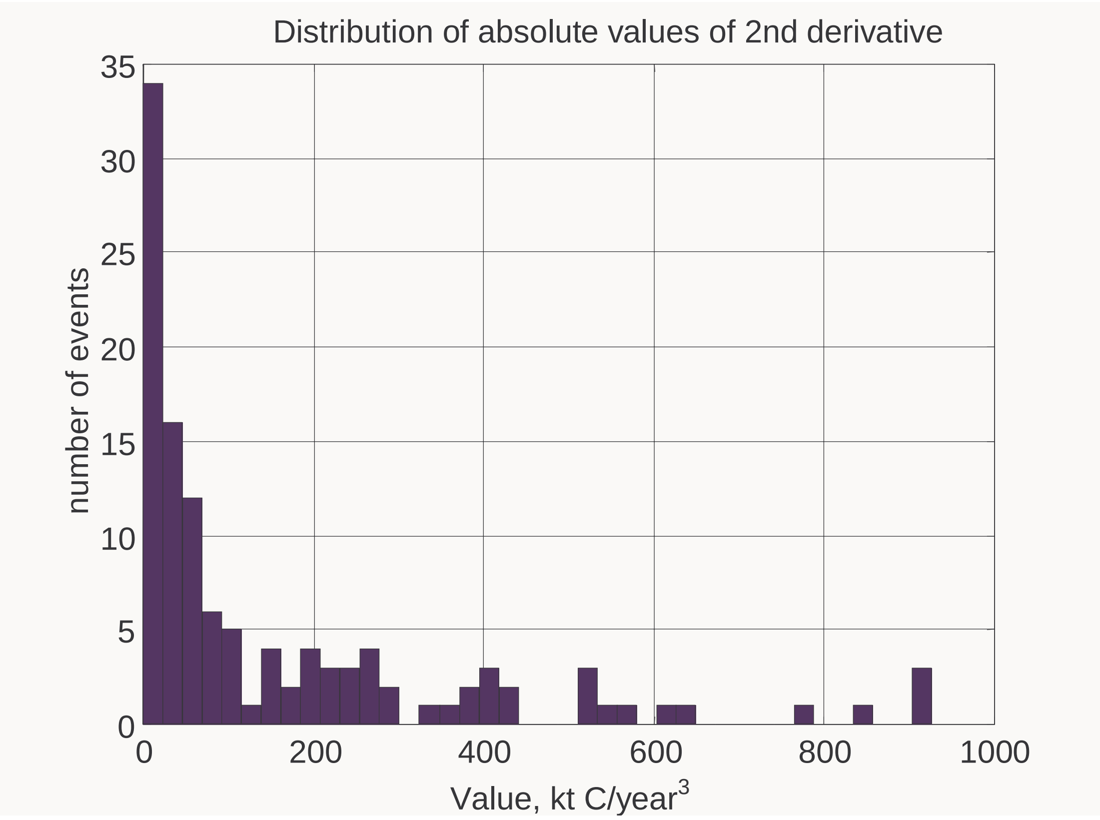


FF and Cement Production CO2 for New Zealand, Fitting
dF/dt(1996)=2.771e+002 kt C/year2
d2F/dt2(1996)=-5.470e+001 kt C/year3
Kilotons of carbon
9500
9000
8500
8000
7500
7000
6500
6000
5500
1990
1995
2000
2005
2010
Year
Fit Err=4.8%

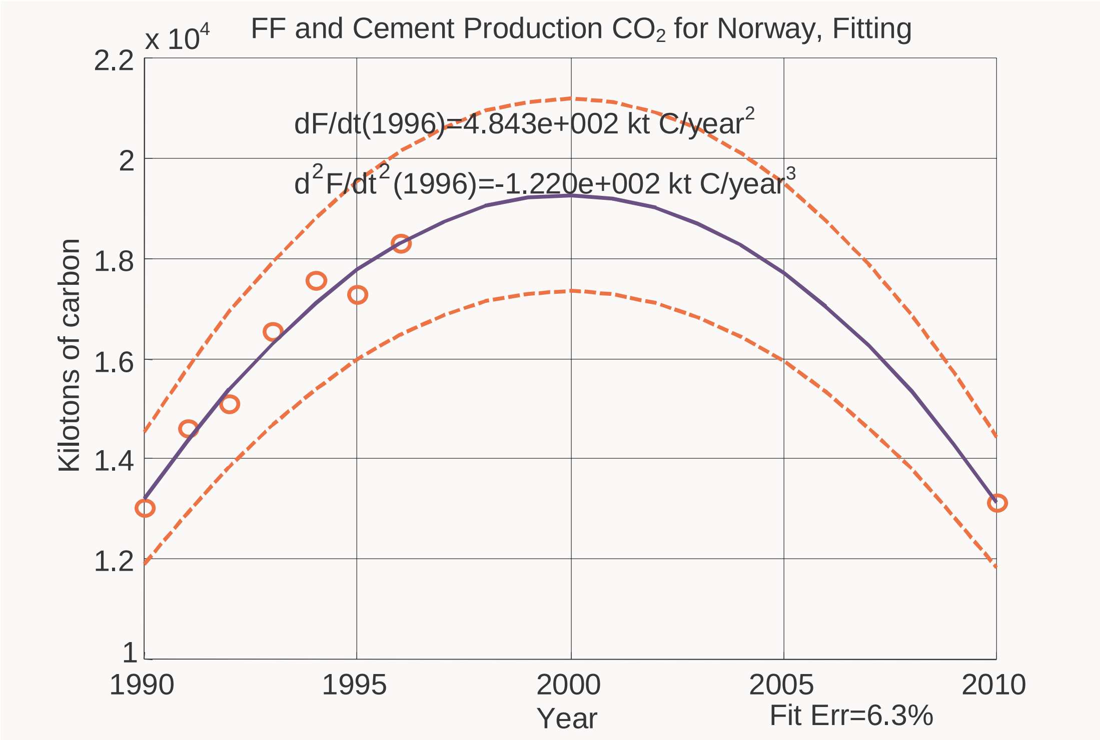


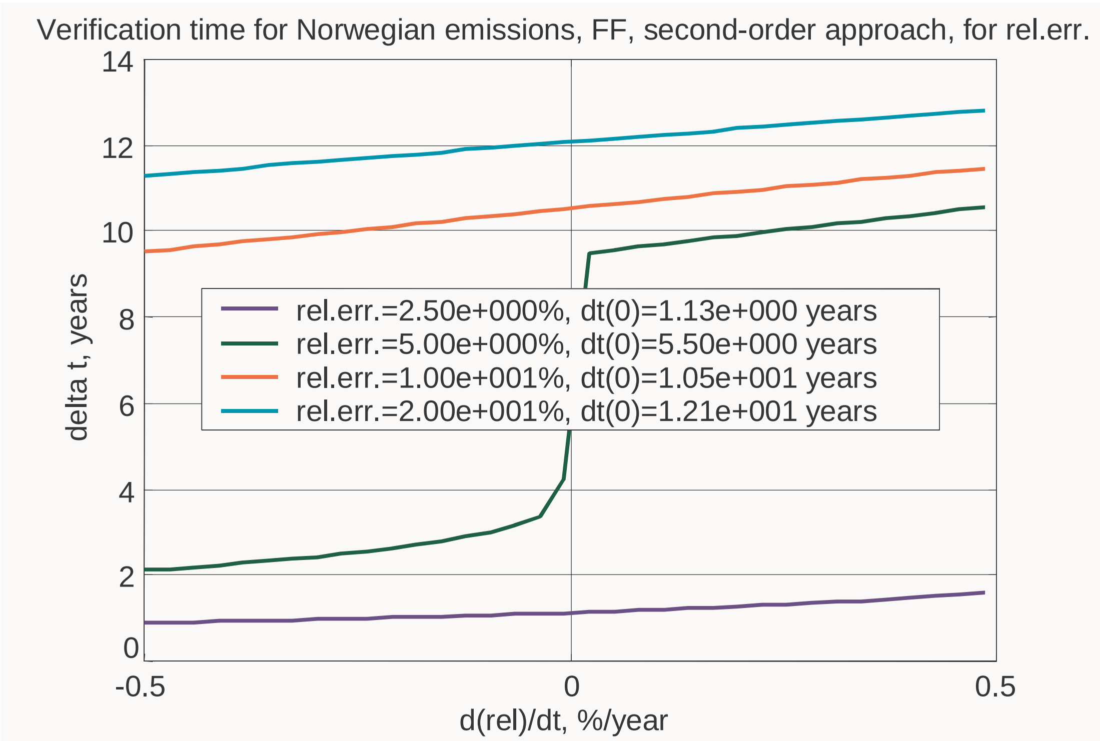
VT for New Zealand emissions, FF, second-order approach, for rel.err.
delta t, years
15
10
5
0
-0.5
0
0.5
d(rel)/dt, %/year
rel.err.=2.50e+000%, dt(0)=7.96e-001 years
rel.err.=5.00e+000%, dt(0)=1.84e+000 years
rel.err.=1.00e+001%, dt(0)=1.23e+001 years
rel.err.=2.00e+001%, dt(0)=1.37e+001 years

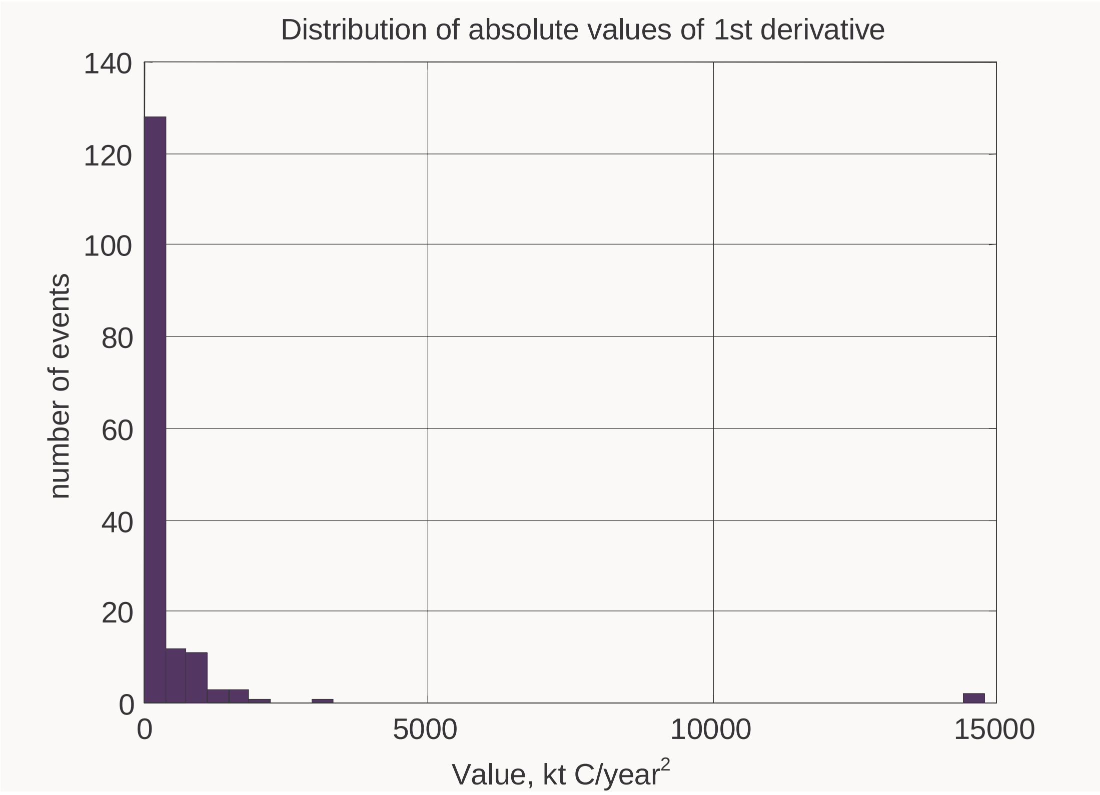

Distribution of absolute values of 1st derivative
number of events
30
25
20
15
10
5
0
0
200
400
600
800
1000
Value, kt C/year2
2

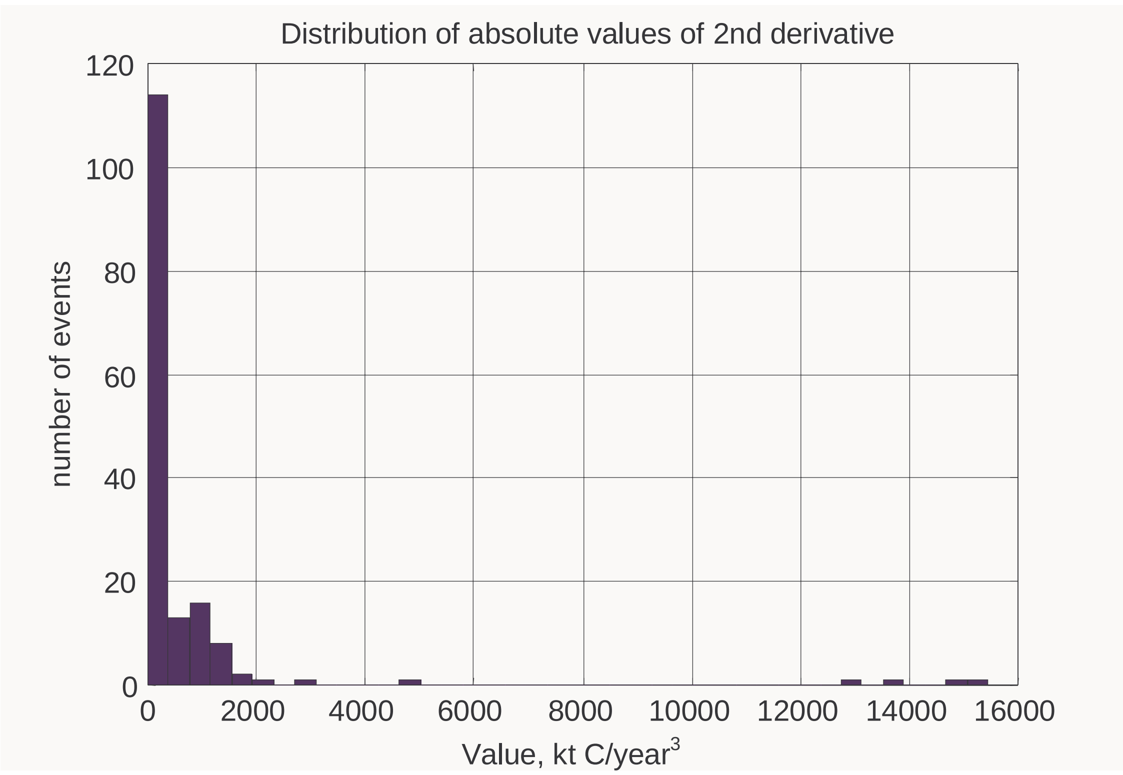

Distribution of absolute values of 2nd derivative
number of events
35
30
25
20
15
10
5
0
0
200
400
600
800
1000
Value, kt C/year3

Norway

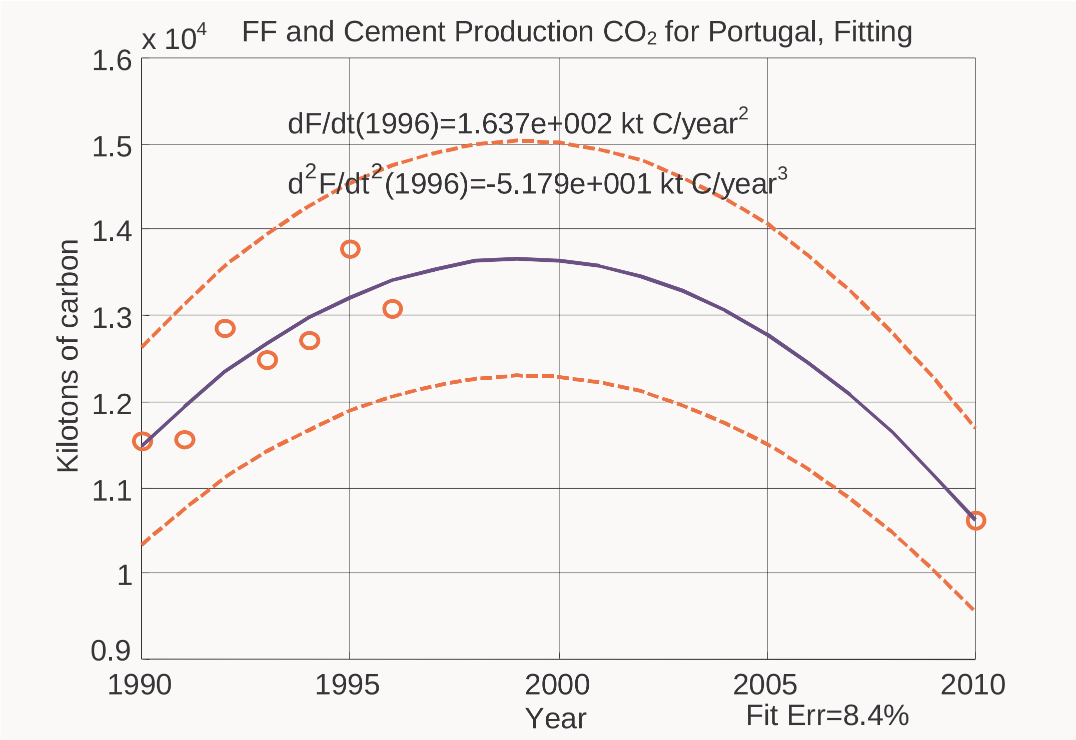

x 10^4
FF and Cement Production CO2 for Norway, Fitting
dF/dt(1996)=4.843e+002 kt C/year^2
d^2F/dt^2(1996)=-1.220e+002 kt C/year^3
Kilotons of carbon
2.2
2
1.8
1.6
1.4
1.2
1
1990
1995
2000
2005
2010
Year
Fit Err=6.3%

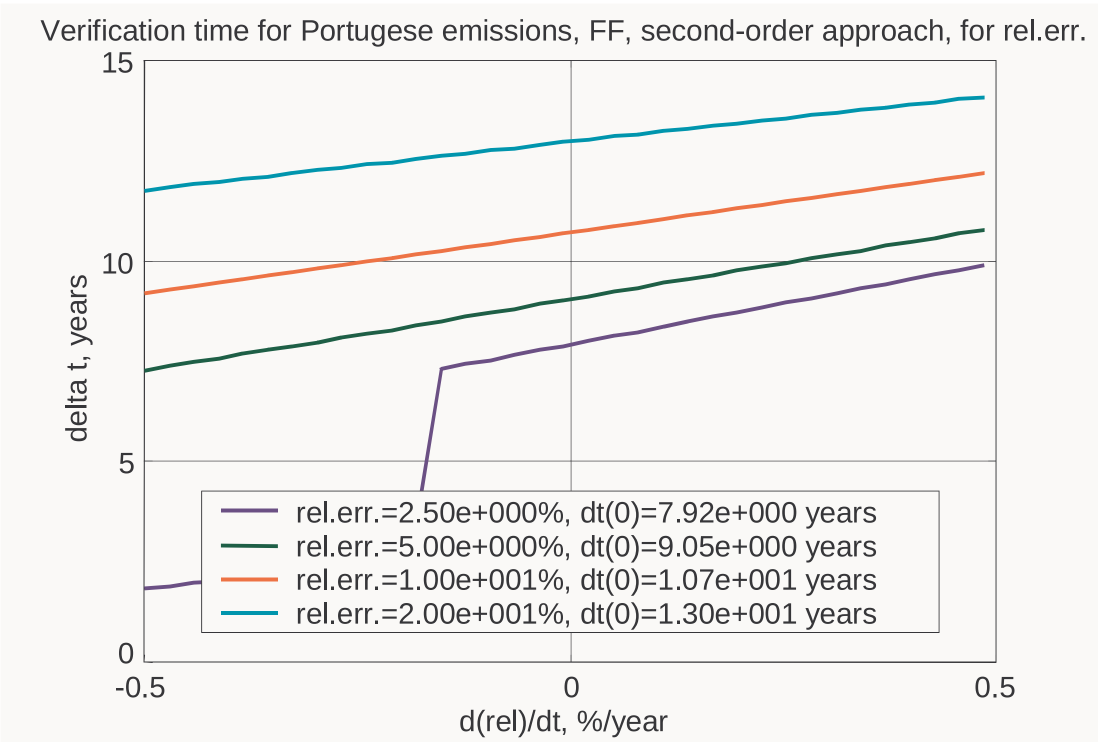

Verification time for Norwegian emissions, FF, second-order approach, for rel.err.
delta t, years
14
12
10
8
6
4
2
0
rel.err.=2.50e+000%, dt(0)=1.13e+000 years
rel.err.=5.00e+000%, dt(0)=5.50e+000 years
rel.err.=1.00e+001%, dt(0)=1.05e+001 years
rel.err.=2.00e+001%, dt(0)=1.21e+001 years
-0.5
0
0.5
d(rel)/dt, %/year

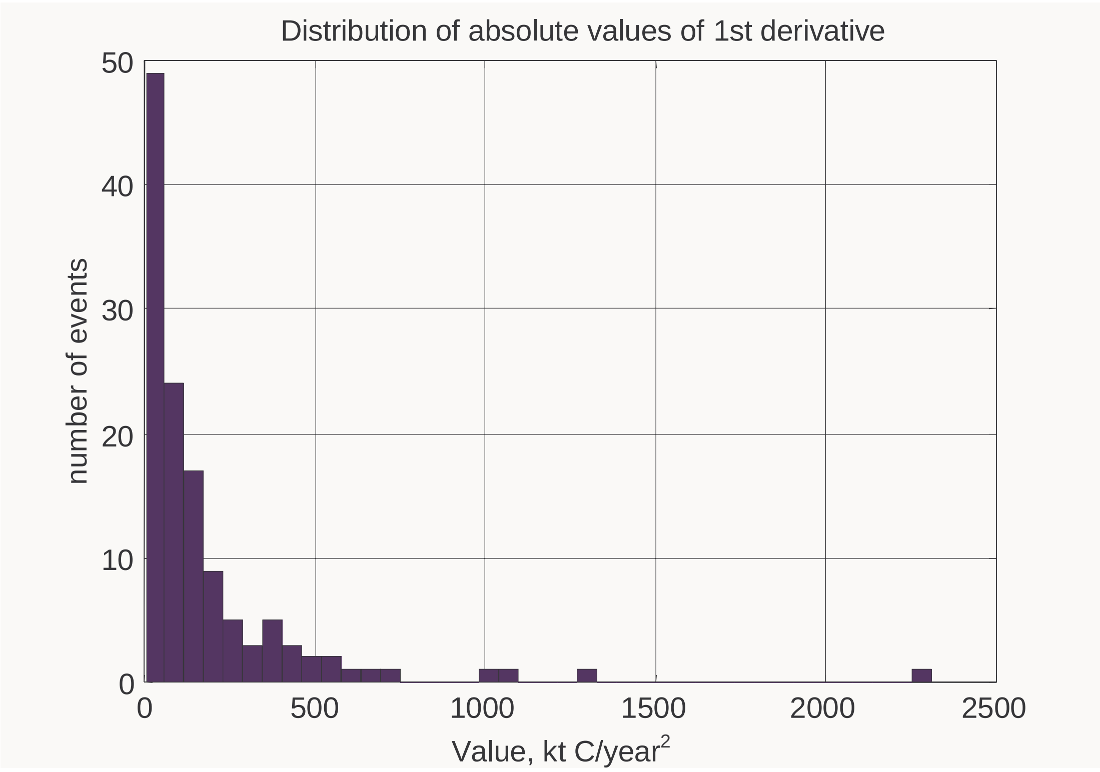

Distribution of absolute values of 1st derivative
number of events
0
20
40
60
80
100
120
140
0
5000
10000
15000
Value, kt C/year2

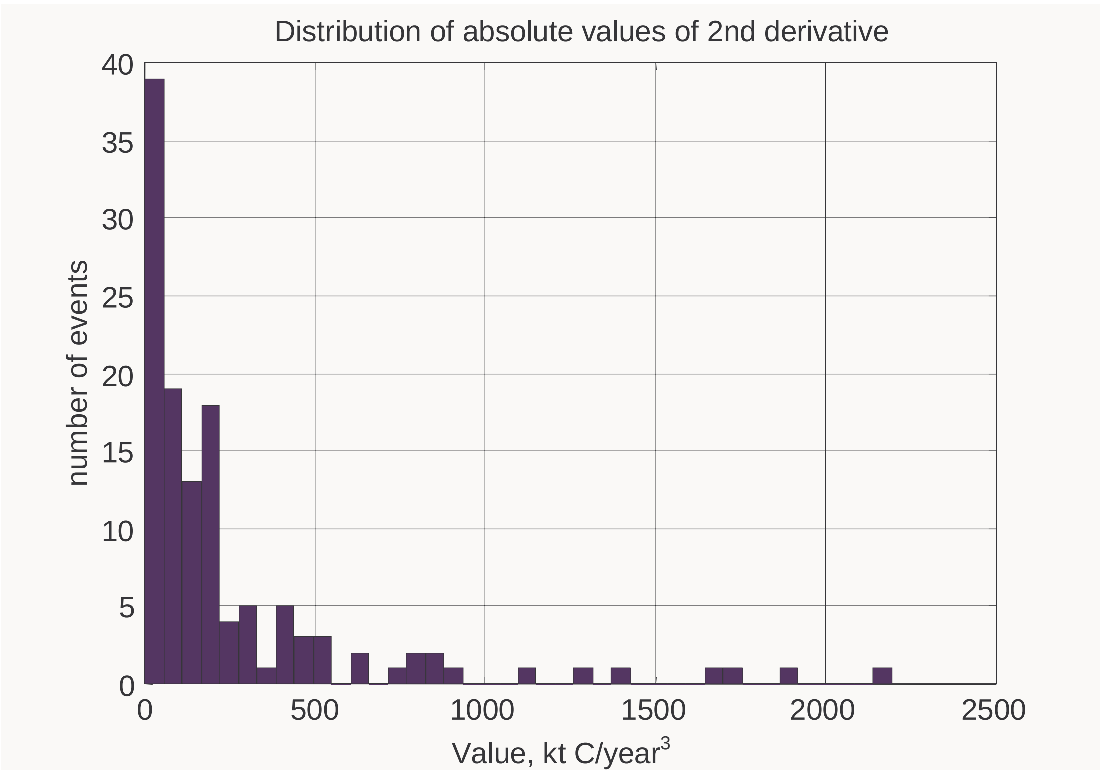

Distribution of absolute values of 2nd derivative
number of events
0
20
40
60
80
100
120
0
2000
4000
6000
8000
10000
12000
14000
16000
Value, kt C/year3

Portugal

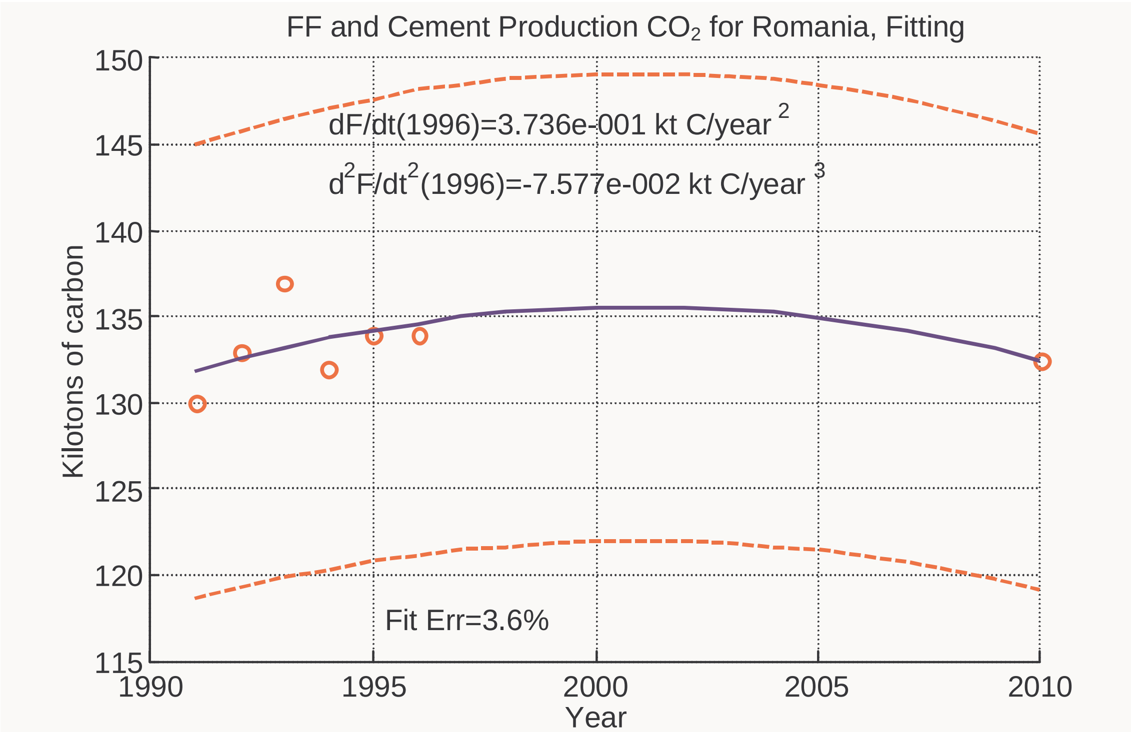

x 10^4
FF and Cement Production CO2 for Portugal, Fitting
dF/dt(1996)=1.637e+002 kt C/year^2
d^2F/dt^2(1996)=-5.179e+001 kt C/year^3
Kilotons of carbon
1.6
1.5
1.4
1.3
1.2
1.1
1
0.9
1990
1995
2000
2005
2010
Year
Fit Err=8.4%


Verification time for Portugese emissions, FF, second-order approach, for rel.err.
delta t, years
15
10
5
0
-0.5
0
0.5
d(rel)/dt, %/year
rel.err.=2.50e+000%, dt(0)=7.92e+000 years
rel.err.=5.00e+000%, dt(0)=9.05e+000 years
rel.err.=1.00e+001%, dt(0)=1.07e+001 years
rel.err.=2.00e+001%, dt(0)=1.30e+001 years

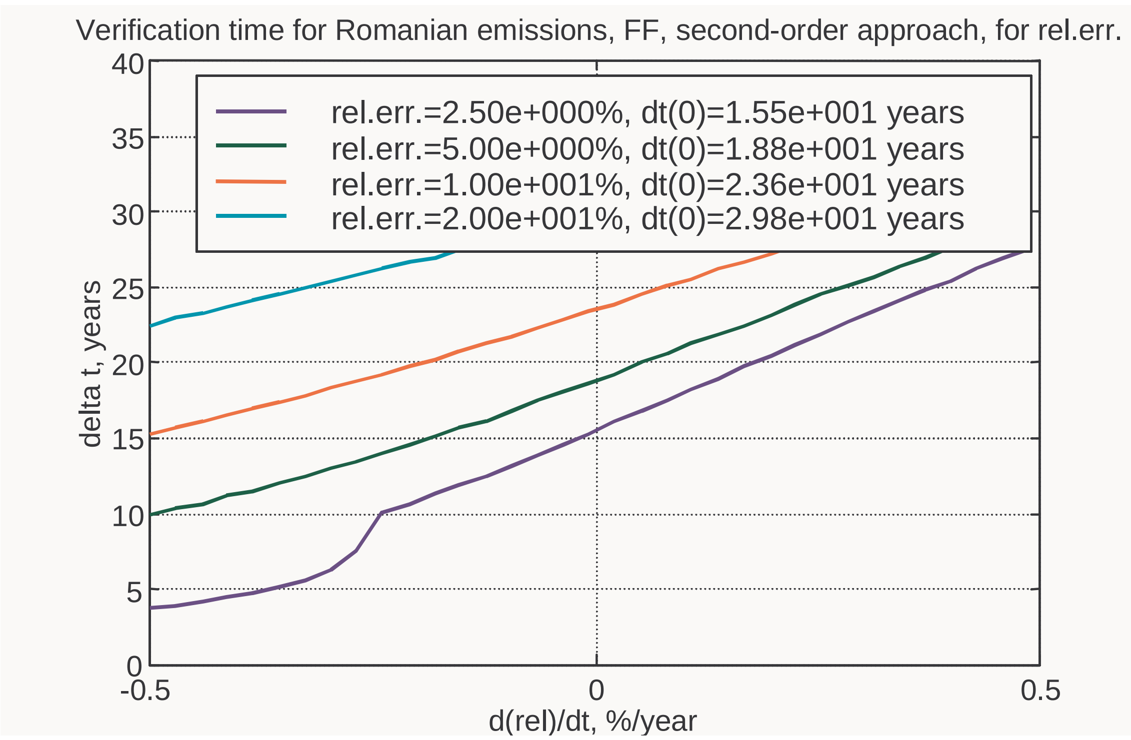

Distribution of absolute values of 1st derivative
number of events
50
40
30
20
10
0
0
500
1000
1500
2000
2500
Value, kt C/year^2


Distribution of absolute values of 2nd derivative
number of events
40
35
30
25
20
15
10
5
0
0
500
1000
1500
2000
2500
Value, kt C/year^3

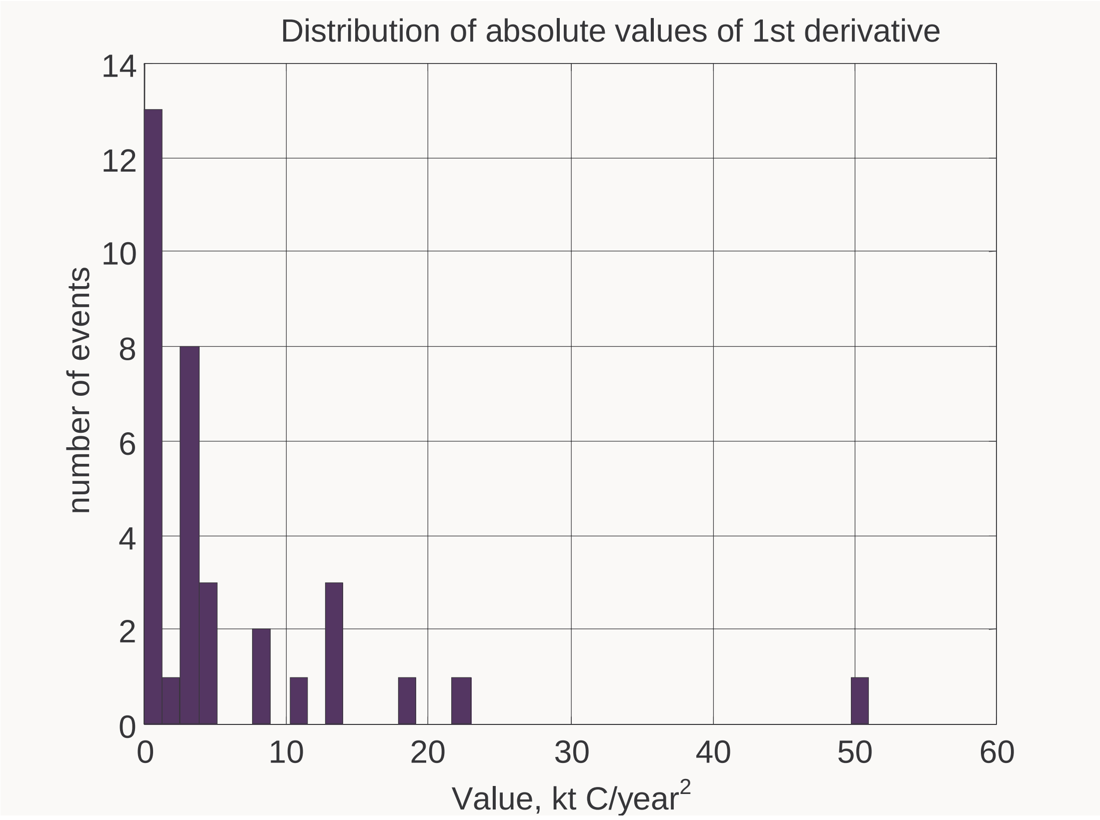
Romania

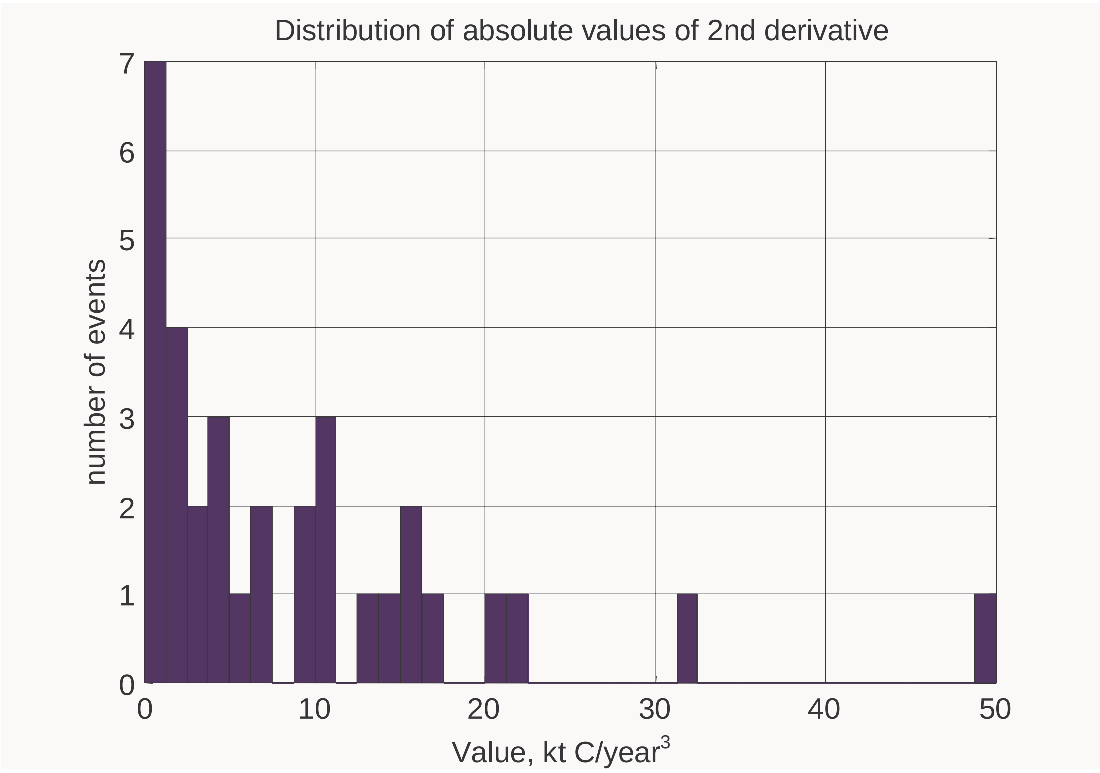


FF and Cement Production CO_2 for Romania, Fitting
dF/dt(1996)=3.736e-001 kt C/year 2
d2F/dt2(1996)=-7.577e-002 kt C/year 3
Fit Err=3.6%
Kilotons of carbon
Year
150
145
140
135
130
125
120
115
1990
1995
2000
2005
2010

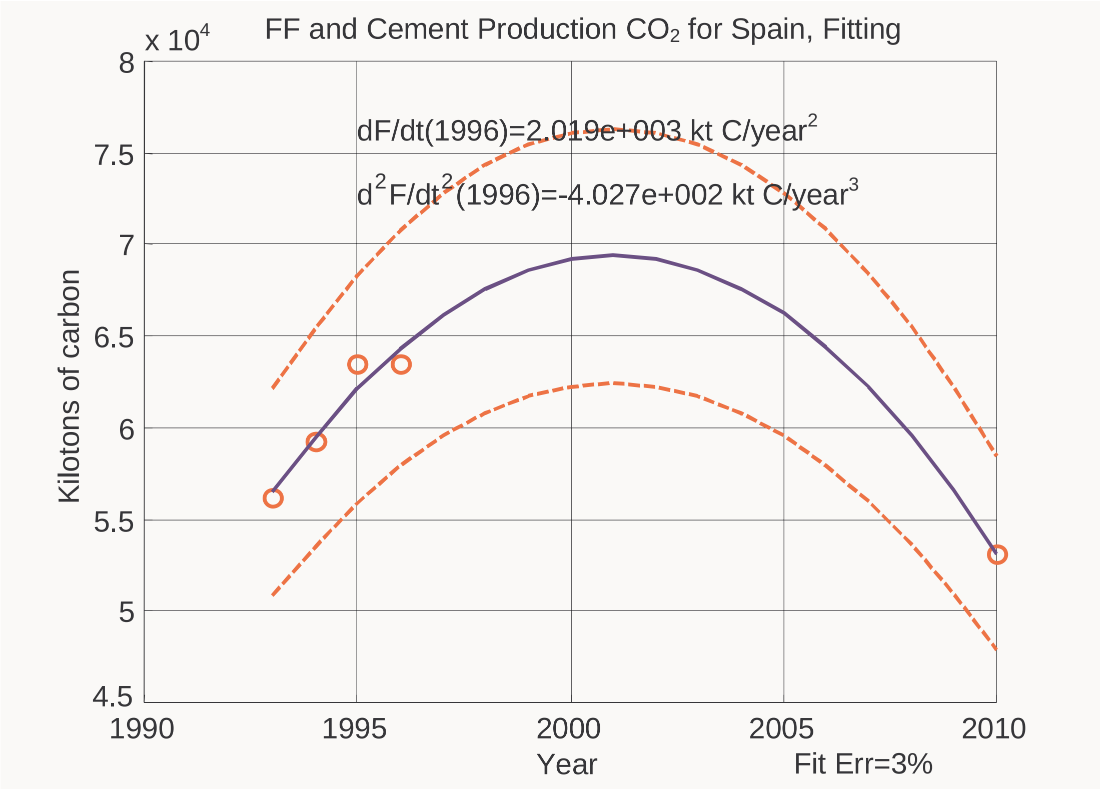


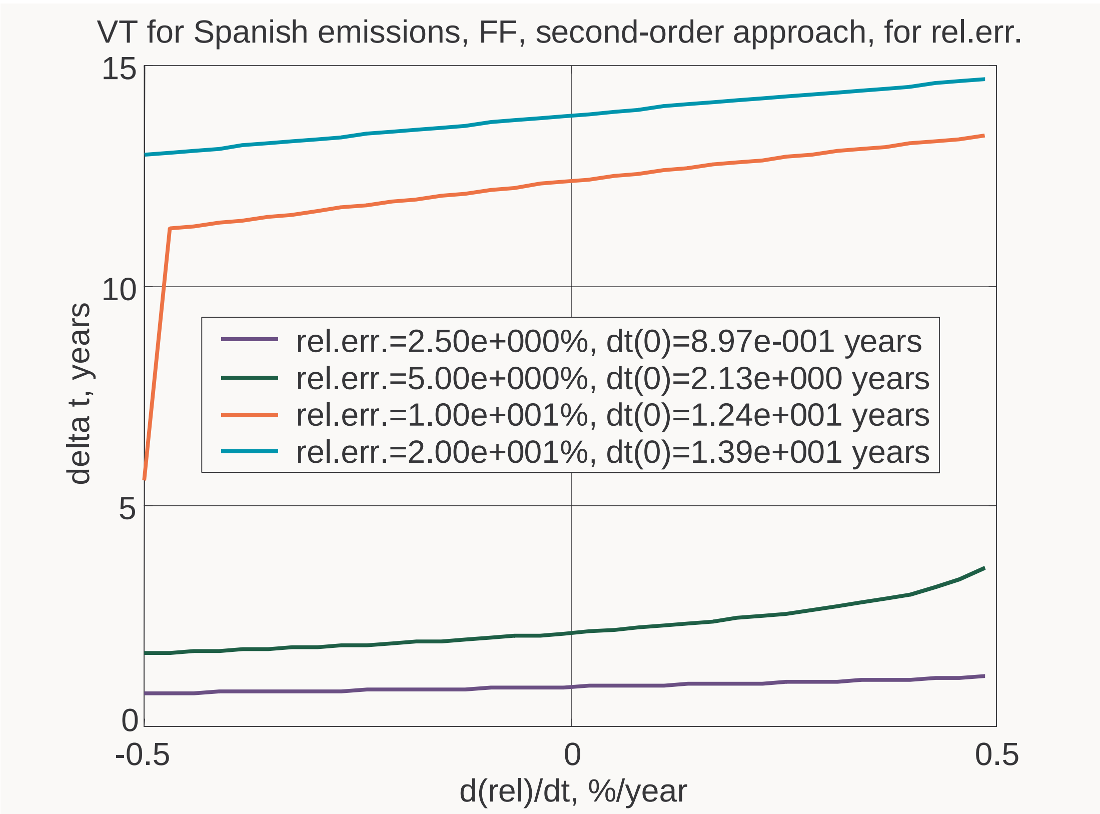
Verification time for Romanian emissions, FF, second-order approach, for rel.err.
rel.err.=2.50e+000%, dt(0)=1.55e+001 years
rel.err.=5.00e+000%, dt(0)=1.88e+001 years
rel.err.=1.00e+001%, dt(0)=2.36e+001 years
rel.err.=2.00e+001%, dt(0)=2.98e+001 years
delta t, years
d(rel)/dt, %/year
40
35
30
25
20
15
10
5
0
-0.5
0
0.5

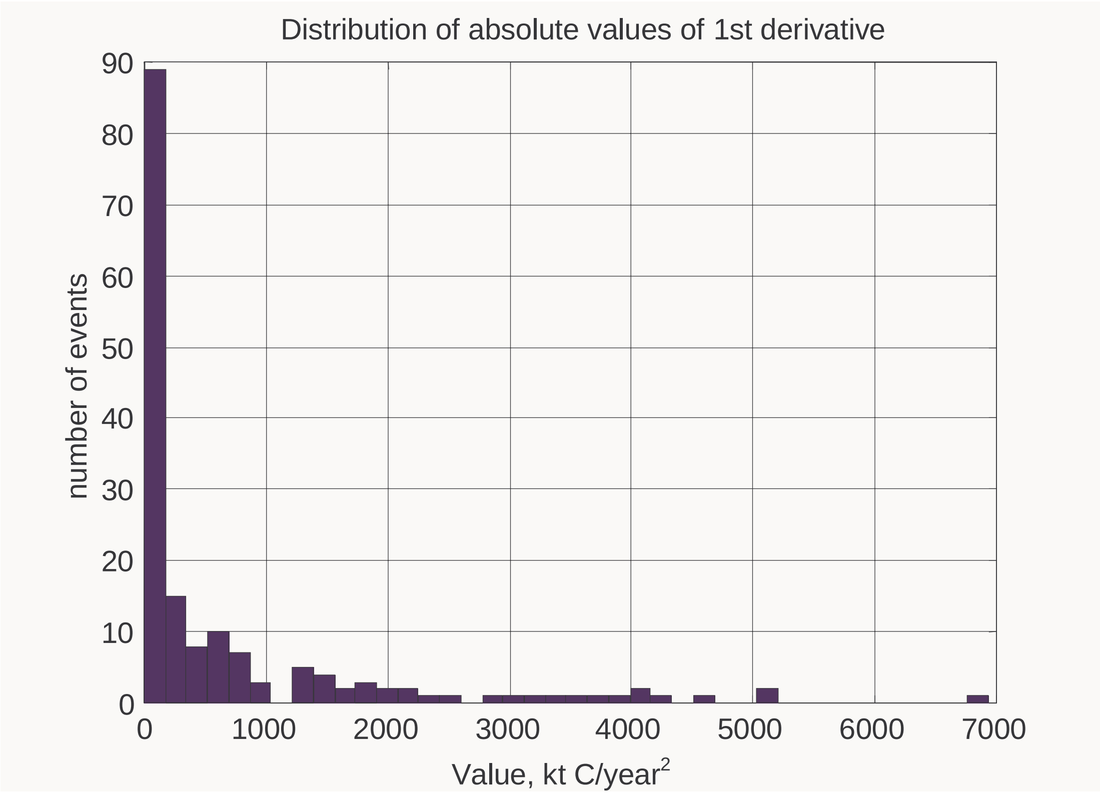

Distribution of absolute values of 1st derivative
number of events
Value, kt C/year^2
0
2
4
6
8
10
12
14
0
10
20
30
40
50
60

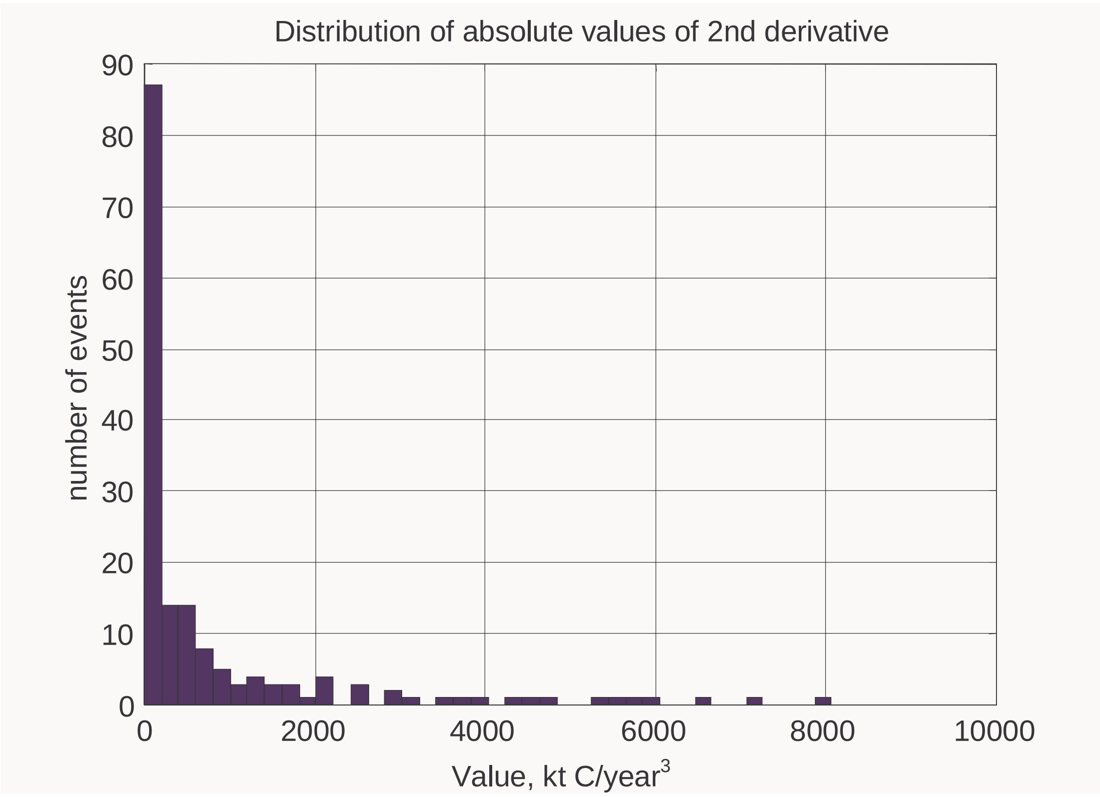

Distribution of absolute values of 2nd derivative
number of events
Value, kt C/year^3
0
1
2
3
4
5
6
7
0
10
20
30
40
50

Spain

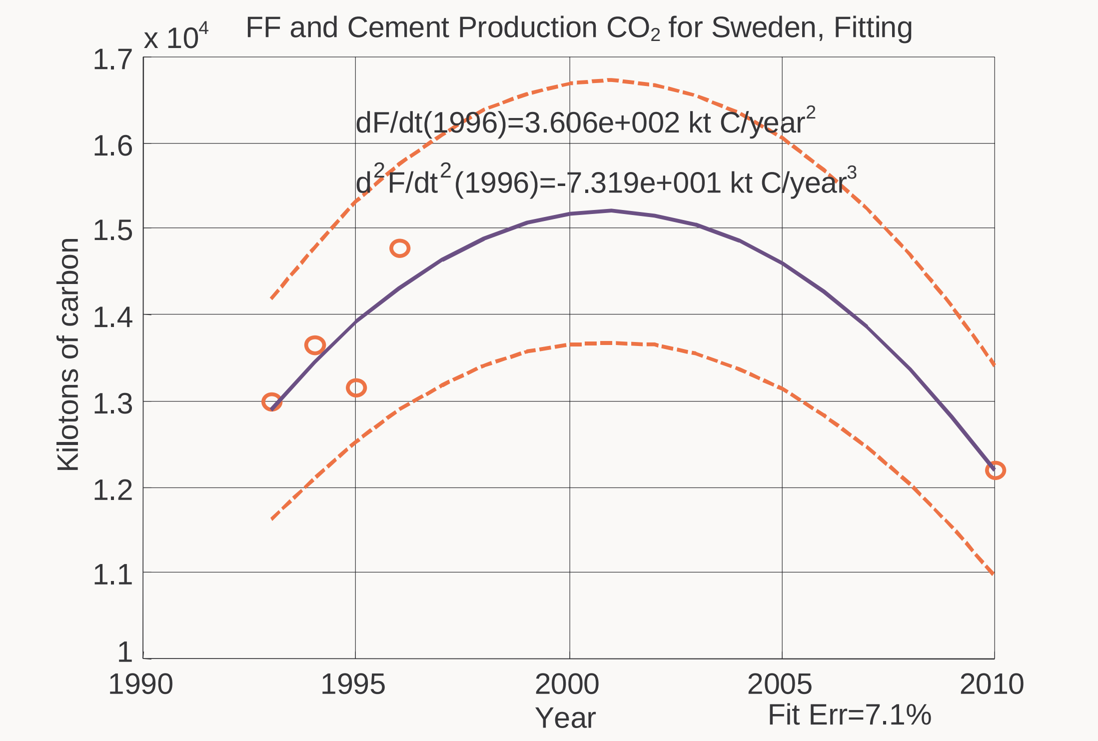

FF and Cement Production CO_2 for Spain, Fitting
x 10^4
8
7.5
7
6.5
6
5.5
5
4.5
Kilotons of carbon
dF/dt(1996)=2.019e+003 kt C/year^2
d^2F/dt^2(1996)=-4.027e+002 kt C/year^3
1990
1995
2000
2005
2010
Year
Fit Err=3%


VT for Spanish emissions, FF, second-order approach, for rel.err.
15
10
5
0
delta t, years
rel.err.=2.50e+000%, dt(0)=8.97e-001 years
rel.err.=5.00e+000%, dt(0)=2.13e+000 years
rel.err.=1.00e+001%, dt(0)=1.24e+001 years
rel.err.=2.00e+001%, dt(0)=1.39e+001 years
-0.5
0
0.5
d(rel)/dt, %/year

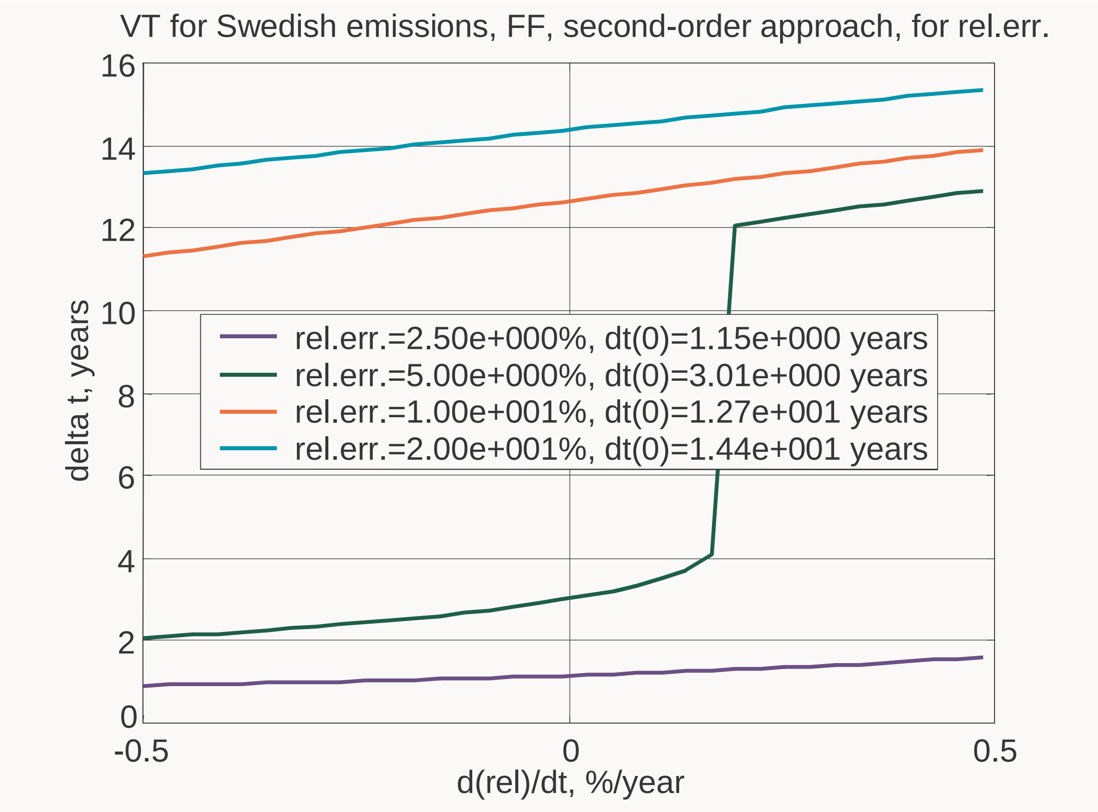

Distribution of absolute values of 1st derivative
number of events
Value, kt C/year2


Distribution of absolute values of 2nd derivative
number of events
Value, kt C/year3

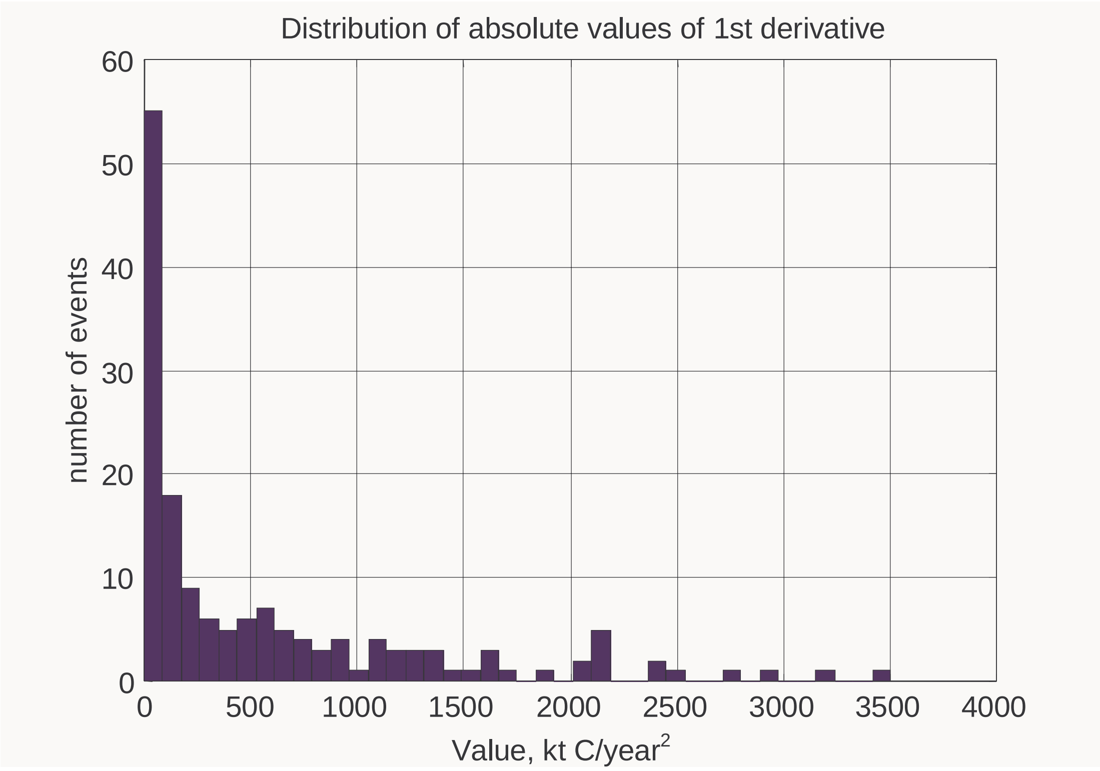
Sweden

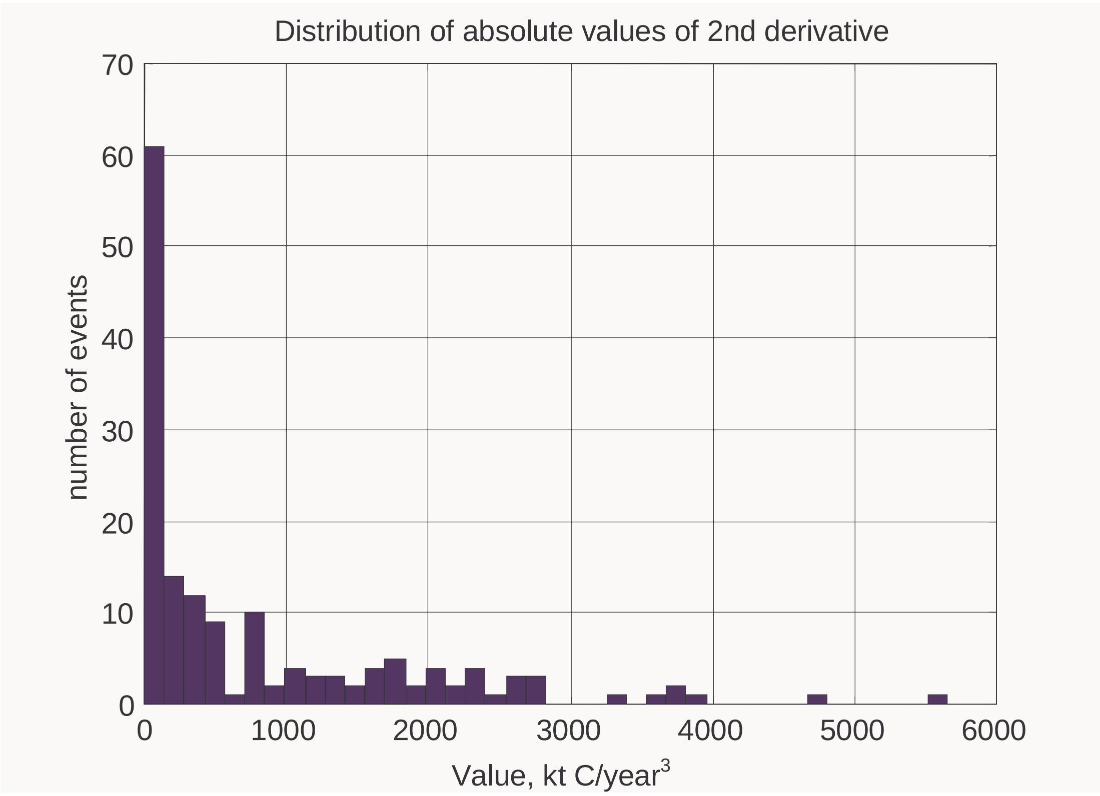


x 10^4
FF and Cement Production CO2 for Sweden, Fitting
dF/dt(1996)=3.606e+002 kt C/year^2
d^2F/dt^2(1996)=-7.319e+001 kt C/year^3
Kilotons of carbon
1.7
1.6
1.5
1.4
1.3
1.2
1.1
1
1990
1995
2000
2005
2010
Year
Fit Err=7.1%

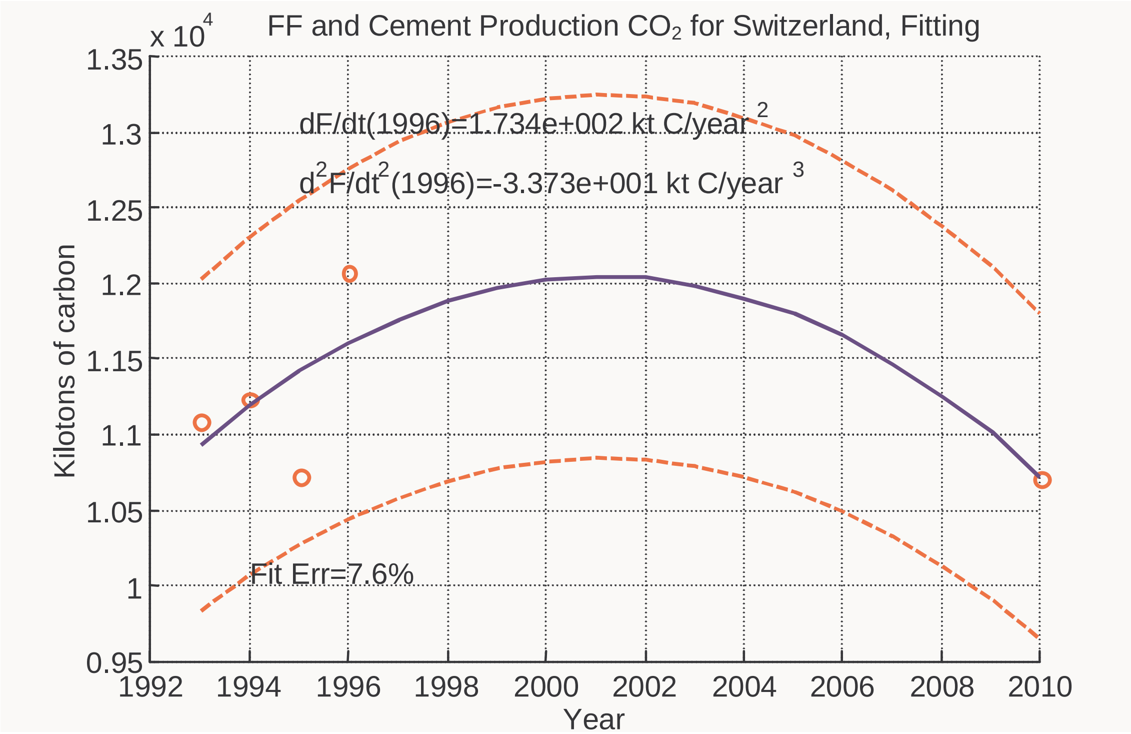


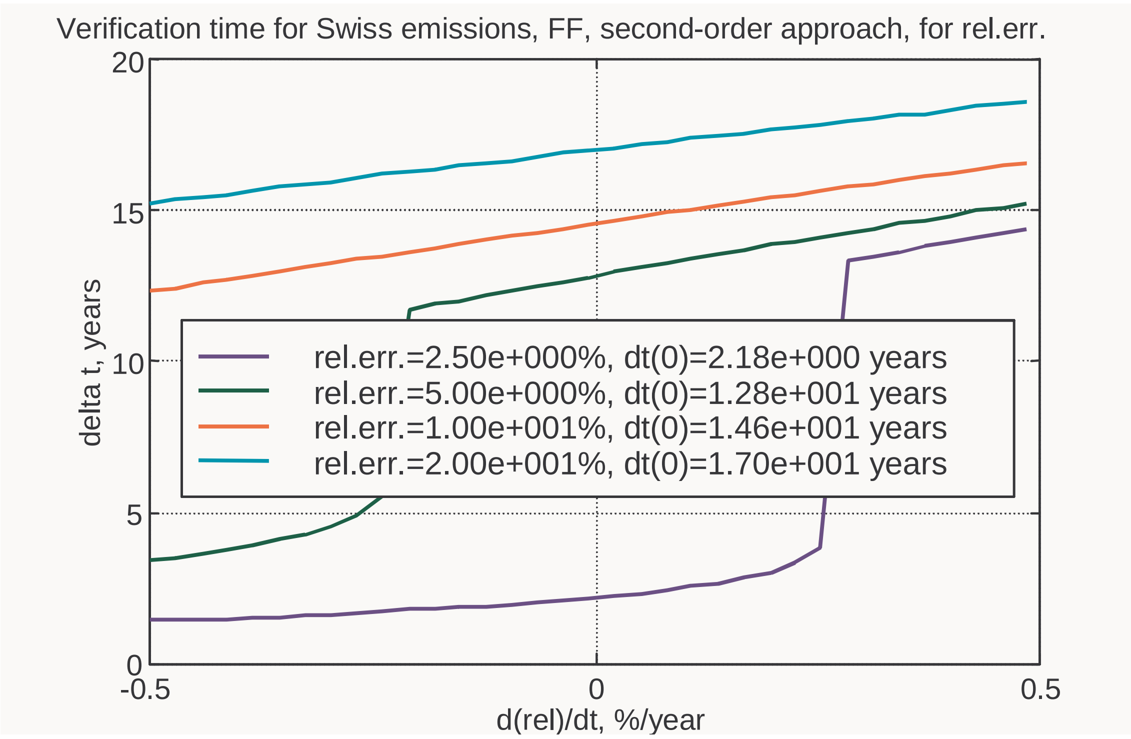
VT for Swedish emissions, FF, second-order approach, for rel.err.
delta t, years
16
14
12
10
8
6
4
2
0
-0.5
0
0.5
d(rel)/dt, %/year
rel.err.=2.50e+000%, dt(0)=1.15e+000 years
rel.err.=5.00e+000%, dt(0)=3.01e+000 years
rel.err.=1.00e+001%, dt(0)=1.27e+001 years
rel.err.=2.00e+001%, dt(0)=1.44e+001 years

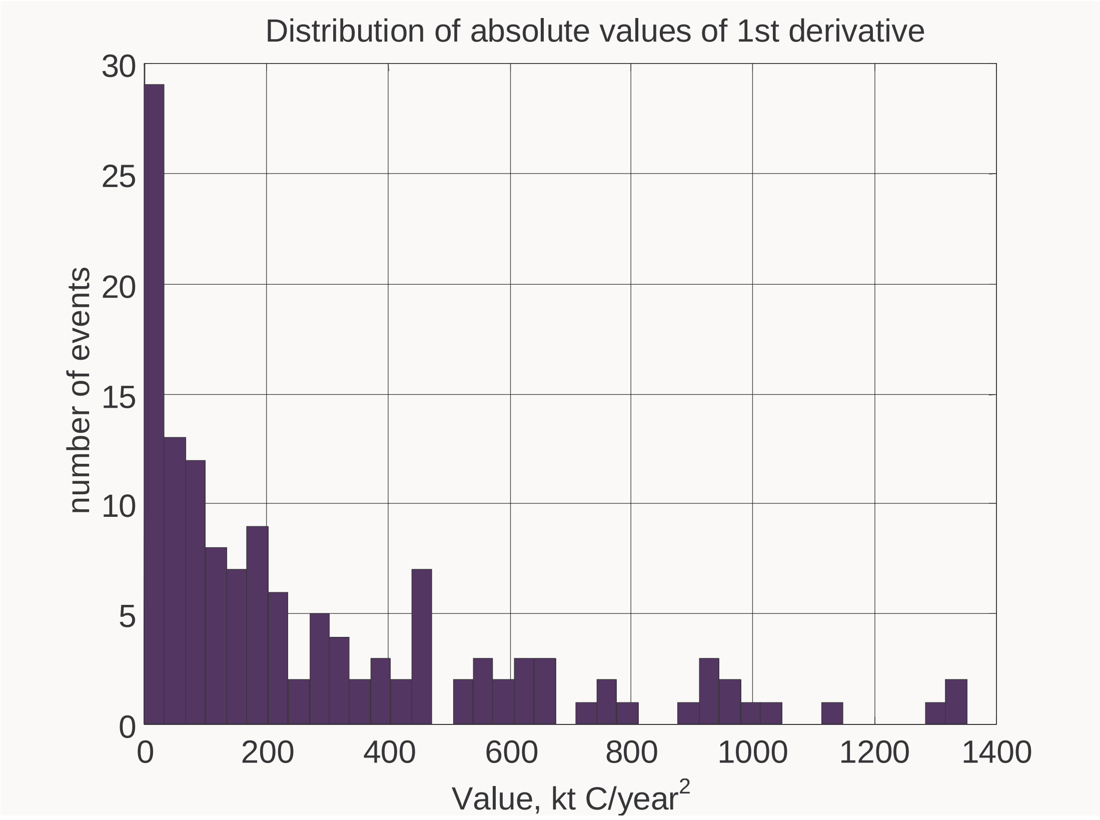

Distribution of absolute values of 1st derivative
number of events
0
10
20
30
40
50
60
0
500
1000
1500
2000
2500
3000
3500
4000
Value, kt C/year2

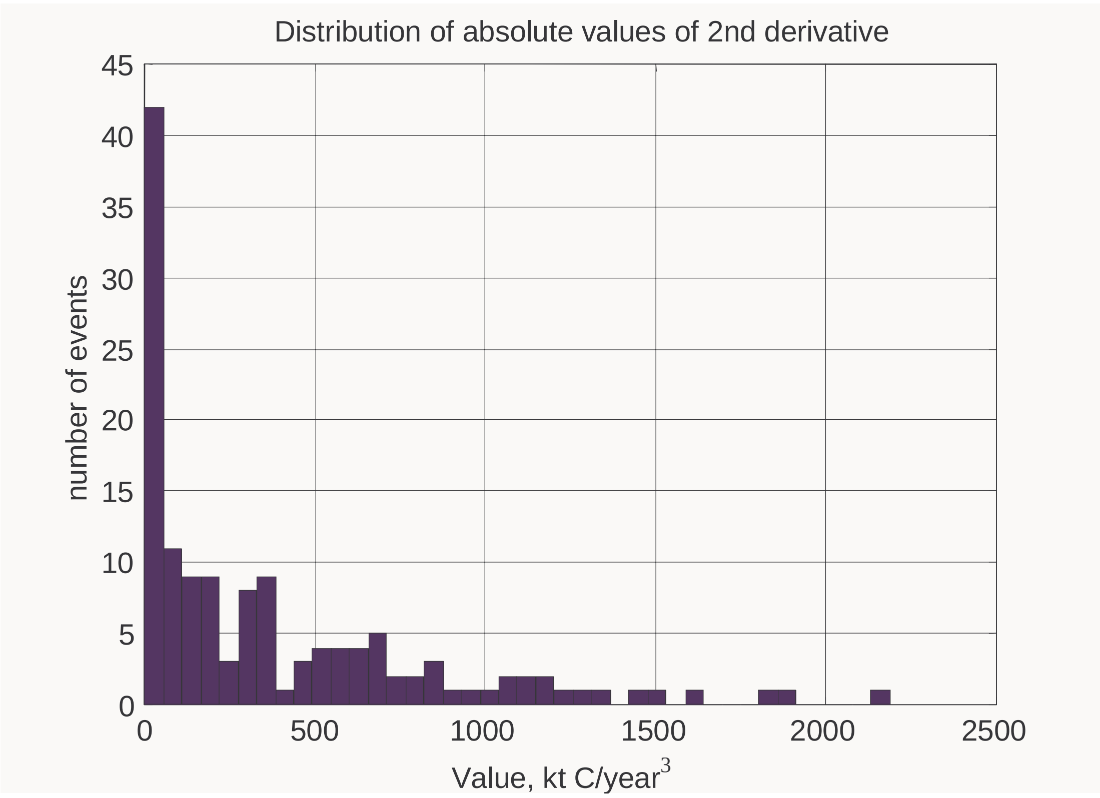

Distribution of absolute values of 2nd derivative
number of events
0
10
20
30
40
50
60
70
0
1000
2000
3000
4000
5000
6000
Value, kt C/year3

Switzerland

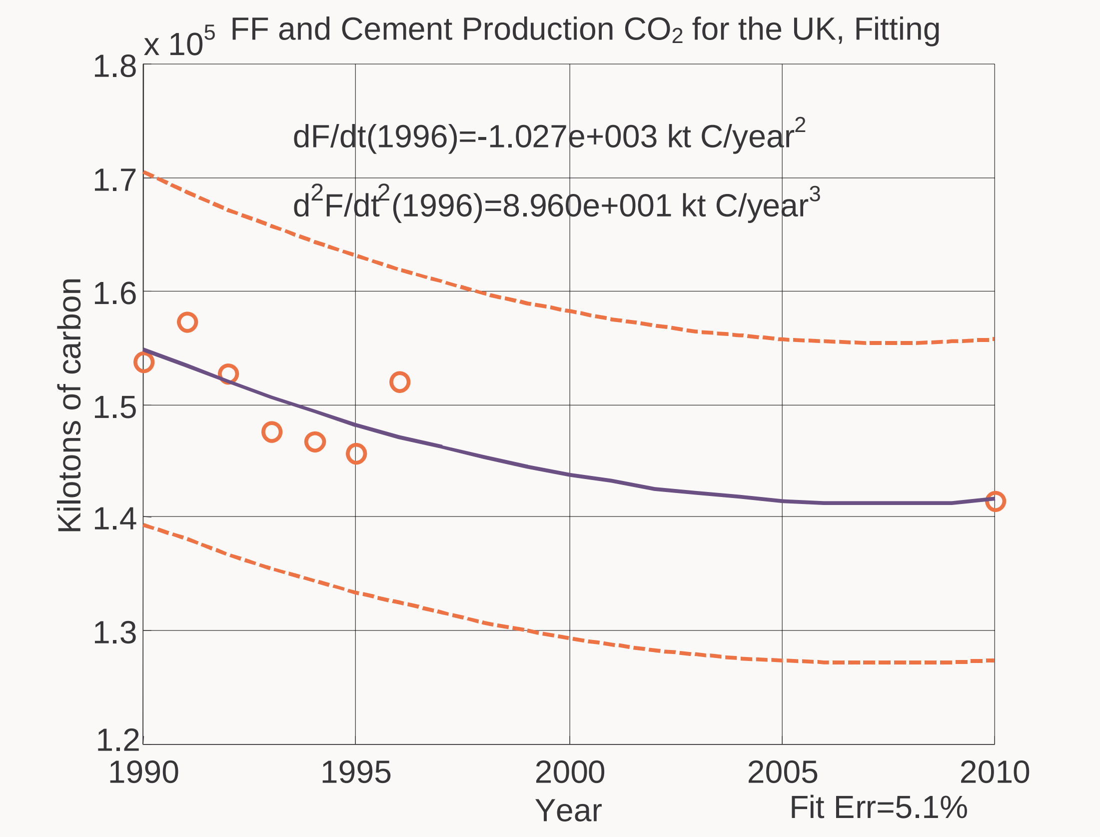


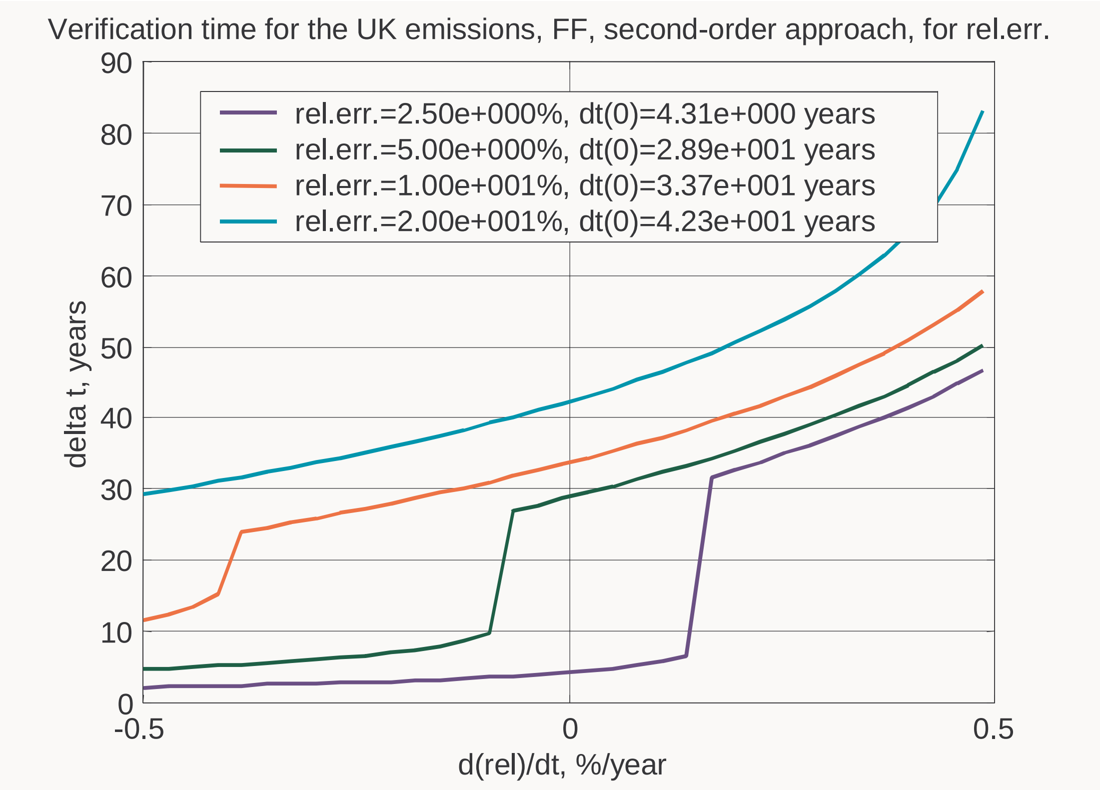


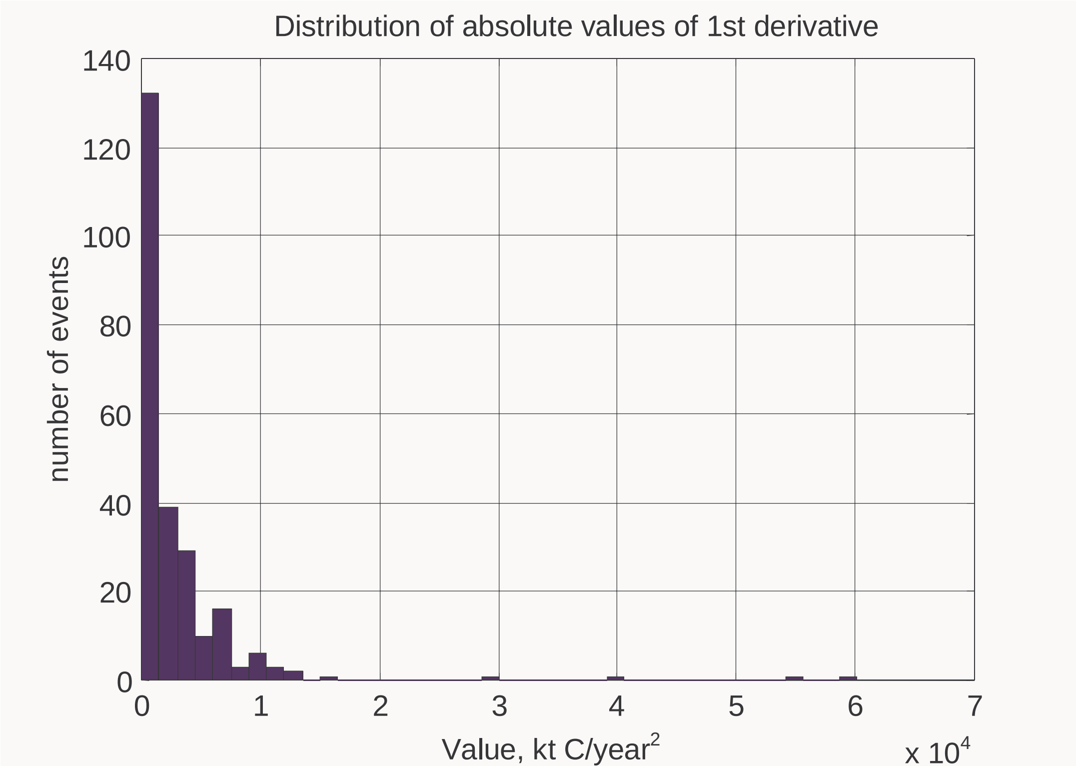

Distribution of absolute values of 1st derivative
number of events
0
5
10
15
20
25
30
0
200
400
600
800
1000
1200
1400
Value, kt C/year2

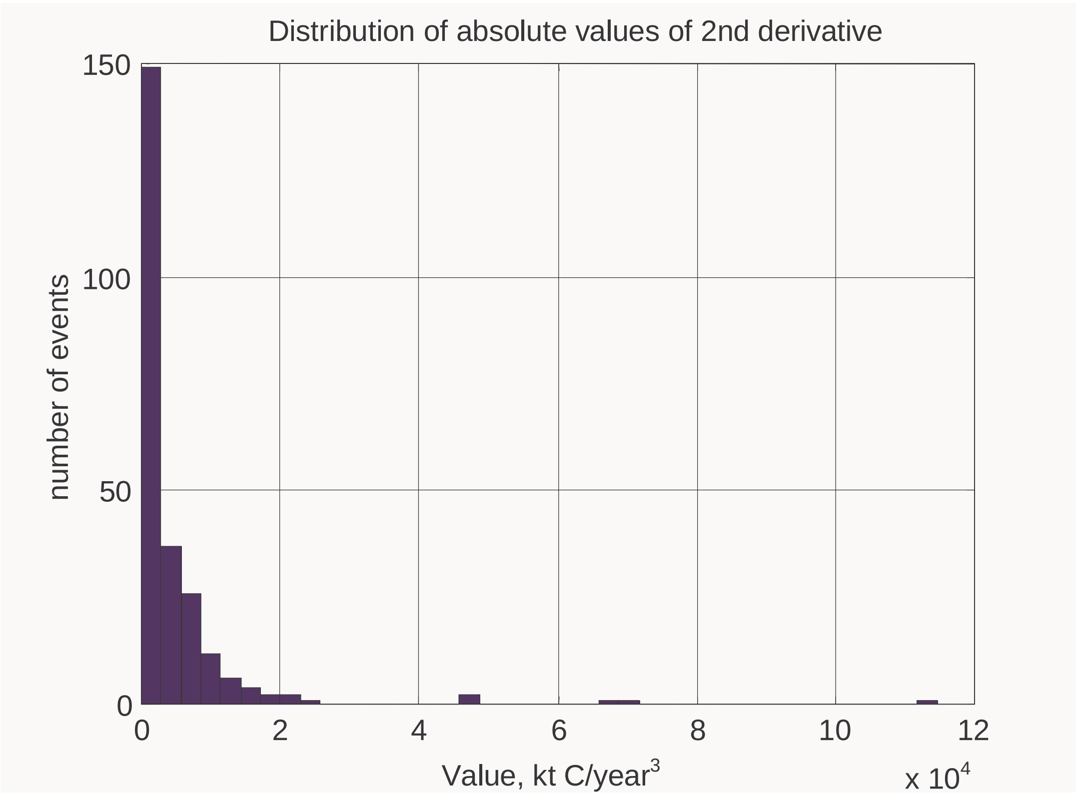

Distribution of absolute values of 2nd derivative
number of events
0
5
10
15
20
25
30
35
40
45
0
500
1000
1500
2000
2500
Value, kt C/year3

United Kingdom

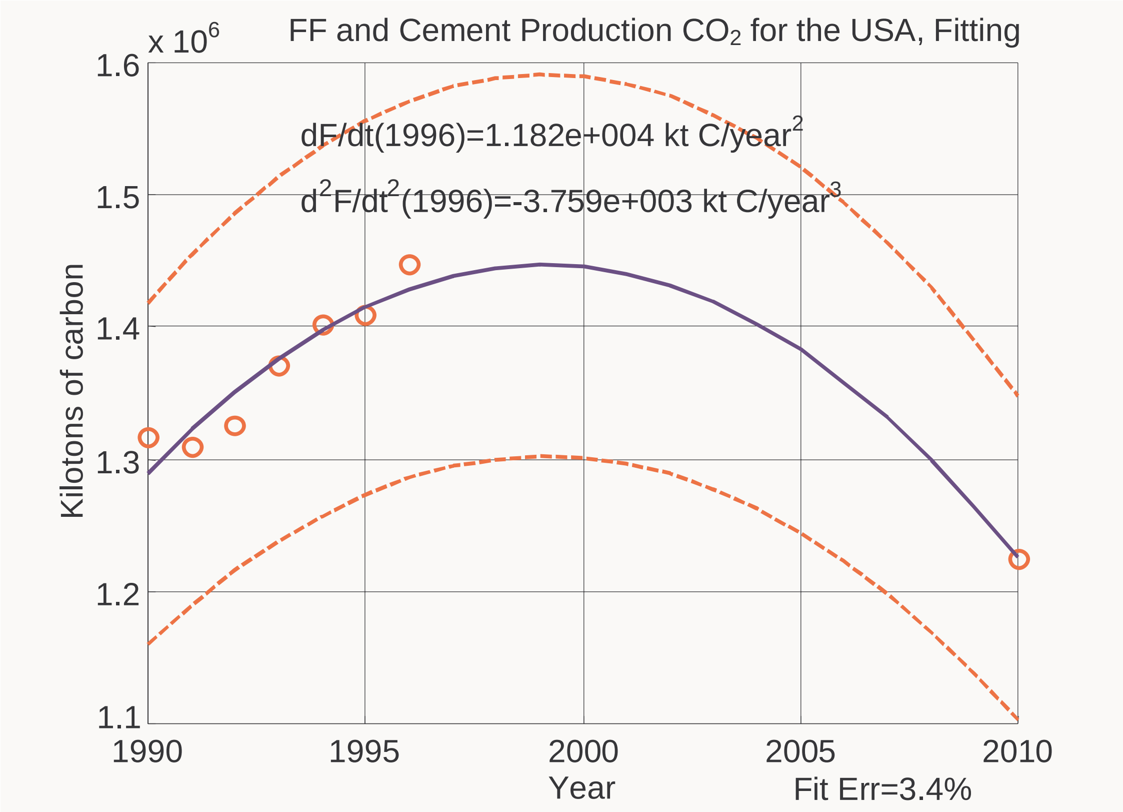


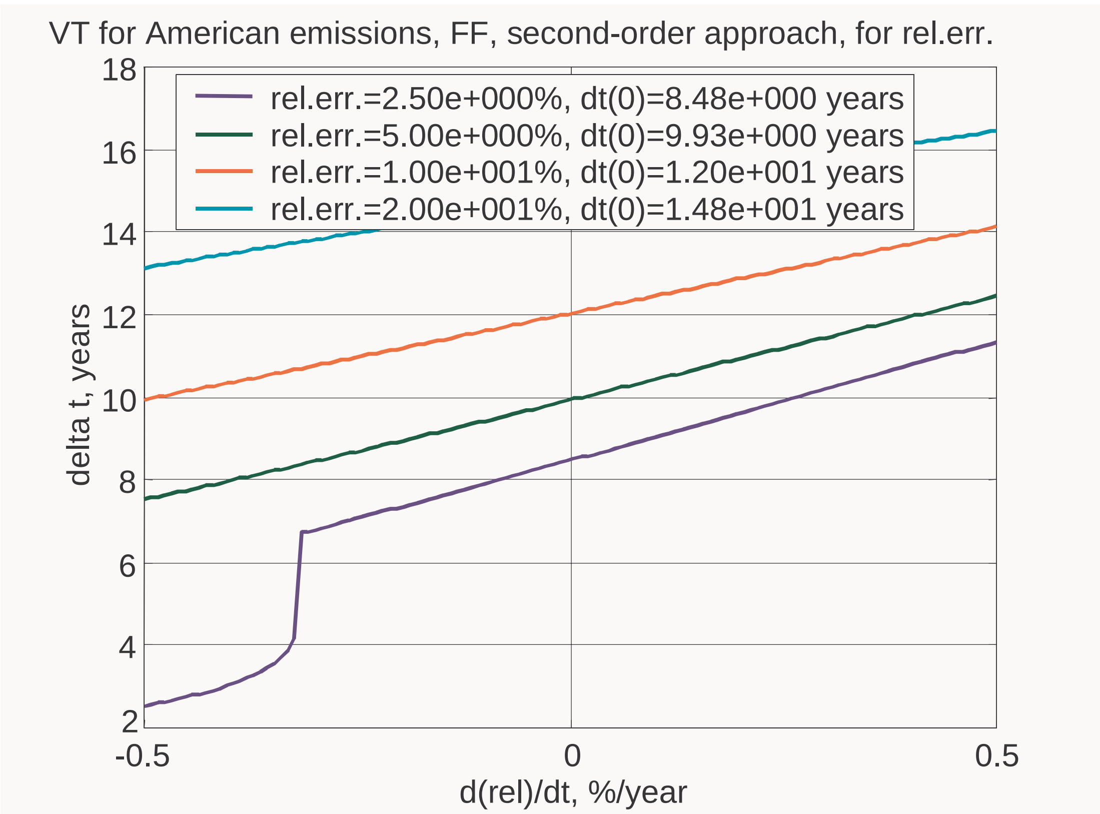


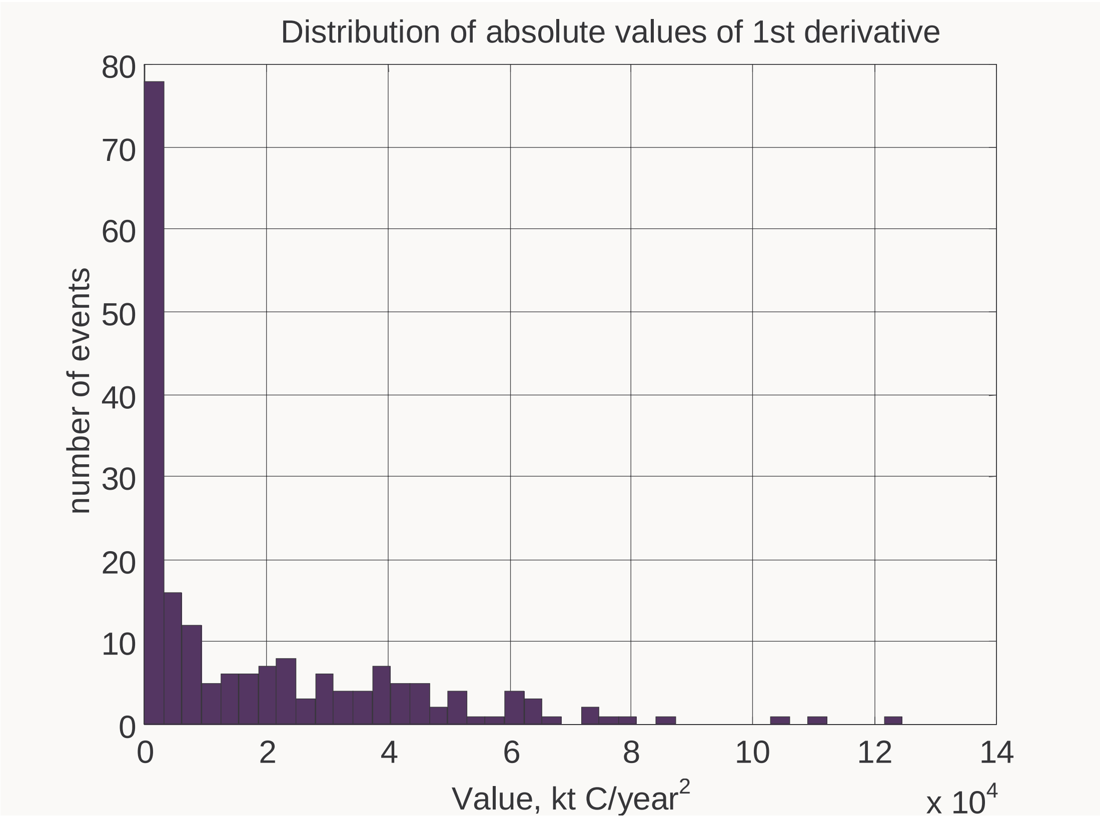

Distribution of absolute values of 1st derivative
number of events
140
120
100
80
60
40
20
0
0
1
2
3
4
5
6
7
Value, kt C/year2
x 10^4

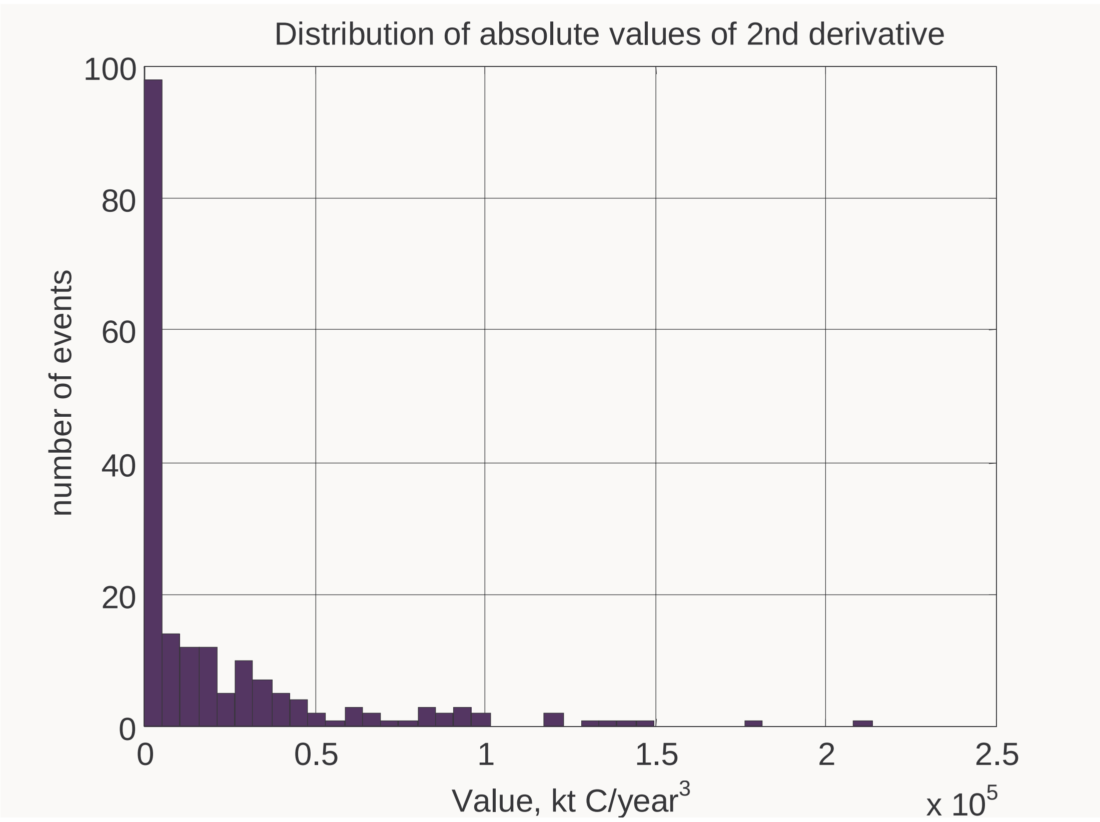

Distribution of absolute values of 2nd derivative
number of events
150
100
50
0
0
2
4
6
8
10
12
Value, kt C/year3
x 10^4

United States of America






Distribution of absolute values of 1st derivative
number of events
Value, kt C/year^2
x 10^4
0
2
4
6
8
10
12
14
0
10
20
30
40
50
60
70
80


Distribution of absolute values of 2nd derivative
number of events
Value, kt C/year^3
x 10^5
0
0.5
1
1.5
2
2.5
0
20
40
60
80
100