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Smoothing time fixed effects

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Smoothing time fixed effects

—PRELIMINARY DRAFT VERSION—

Niklas Gösser ^{*,#} and Nima Moshgbar ^{+,#}

July 2020

Abstract

Controlling for time fixed effects in analyses on longitudinal data by means of time-dummy variables has long been a standard tool in every applied econometrician's toolbox. In order to obtain unbiased estimates, time fixed effects are typically put forward to control for macroeconomic shocks and are (almost) automatically implemented when longitudinal data are analyzed. The applied econometrician's toolbox contains however no standard method to control for time fixed effects when time-dummy variables are not applicable. A number of empirical applications are crucially concerned with both suffering from bias due to omitting time and time-dummies being inapplicable. This paper introduces a simple and readily available parametric approach to approximate time fixed effects in case time dummy variables are not applicable. Applying Monte Carlo simulations, we show that under certain regulatory conditions, trend polynomials (*smoothing time fixed effects*) yield consistent estimates by controlling for time fixed effects, also in cases time-dummy variables are inapplicable. As the introduced approach implies testing nested hypotheses, a standard testing procedure enables the identification of the order of the trend polynomial. Applications that may considerably suffer from bias in case time fixed effects are neglected are among others cartel overcharge estimations, merger and regulation analyses and analyses of economic and financial crises. These applications typically divide time into event and control periods, such that standard time dummies may not be applicable due to perfect multicollinearity. In turn, their estimates of interest most crucially need to be purged from other (unobserved) time dependent factors to be consistent as time may by construction induce omitted-variable bias.

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1. Introduction

Controlling for time fixed effects in empirical models that are based on longitudinal data has long been a standard tool in applied empirical applications.¹ Time fixed effects allow controlling for underlying observable and unobservable systematic differences between observed time units. In applied (micro-) econometric applications, time fixed effects are typically put forward to control for macroeconomic shocks and are (almost) automatically implemented when longitudinal data are analyzed, in order to obtain unbiased estimates. Time fixed effects are standardly obtained by means of time-dummy variables, which control for all time unit-specific effects. This implies controlling for T-1 time-unit dummy variables in case T time periods are observed in the data. Due to different reasons, in many applications the observations are measured on a yearly basis, such that time fixed effects are typically controlled for by T-1 year dummies in case T years are observed in the data.

Time-dummy variables may however be inapplicable in a number of econometric applications due to perfect multicollinearity. For these applications, the applied econometrician's toolbox so far contains no standard method to control for time fixed effects. The lack of controlling for time fixed effects potentially results in considerably biased estimates, especially in case the variables of interest are measured conditional on time. This paper introduces a simple and readily available parametric approach to control for time fixed effects in case time-dummy variables are not applicable.²

Applications that may especially suffer from bias due to the omission of time fixed effects in the literature as well as in practitioners' applications are cartel overcharge estimations, merger and regulation analyses and analyses of economic and financial crises. In these applications the typical measurement of events involves dividing time into event and control periods, such that standard time dummies may not be applicable due to perfect multicollinearity. In turn, their estimates of interest are constructed conditional on time and thus by construction need to be purged from all time dependent factors. Time may therefore be regarded as immediate source for omitted-variable bias in these applications.

Applying Monte Carlo simulations, we show that polynomials of the time trend allow for approximating time fixed effects which yield consistent estimates under certain regulatory conditions. Our results show that unbiased estimates can be obtained or at least be approximated under *smoothing time fixed*

¹ We use the term "longitudinal" in order to indicate that some evolution over time is present in the data. Underlying data consistent with our setting can especially be panel data and pooled or repeated cross-sections. Furthermore, we refer to "time-unit fixed effects" simply as "time fixed effects".

² The suggested parametric approach for obtaining time fixed effects without time-dummy variables can be expressed as a special case of generalized additive models (GAM).

effects, especially when unobserved time-dependent factors change smoothly over time. In case time-dummy variables are applicable however, these are clearly superior to smoothing time fixed effects. Applications in which the event of interest is measured as binary variable conditional on time however, time-dummy variables are typically not applicable due to perfect multicollinearity, especially when the event of interest can merely be measured in units of the observable time periods. Our results suggest that in these cases, time-dummy variables may in turn introduce greater bias if applied.

The empirical literature so far has therefore widely ignored time fixed effects instead, despite a clear expectation of potential bias in many cases. Smoothing time fixed effects may introduce a crucial albeit very simple correction in many applications, in which time-dummies would otherwise introduce additional bias in the estimates. The proposed parametric approach of smoothing time fixed effects does not make any assumptions about the form or magnitude of the unobserved time-dependent effects. The order of the trend polynomials however needs to be determined by the user. As the introduced parametric approach implies testing for nested hypotheses, standard F-tests may guide determining the order of the trend polynomial that is underlying the data generating process.

Many applications relevant in economic research are concerned with perfect multicollinearity when time-dummies are included as new regulatory requirements usually start at the beginning of the year or month and, in general, business decisions are usually made for a full calendar year. Yet, economic time series are often available merely on the level of the very same time periods. On the one hand economic time series are usually not available on high frequencies of for example a daily or weekly basis. On the other hand, many events may not be traced back to a precise starting point, such that the measurement might be based on an available definition of time merely due to pragmatical reasons.³

In empirical analyses of economic relations, the underlying time series usually tend to be highly correlated over time, such that a minimal smoothing requirement is often naturally met. In addition, time fixed effects also capture all time-unit specific effects, that may be observable or unobservable or at least unobservable to the researcher.⁴ The trend variable measuring time can then be included in the regression equation linearly, quadratically or as higher polynomial approximating the otherwise discrete steps of time-dummies.⁵ In turn, with smoothing time fixed effects perfect multicollinearity of time-dummy variables can be overcome, while retaining the purging properties of time fixed effects.

³ One example is the financial crisis. It is difficult to define a clear starting point for different industries and countries.

⁴ This may also apply to other field of research such as in social sciences in general. Wherever it is applied and a period of time is observed, this problem arises.

⁵ Similar to time-dummy variables, only T-2 polynomials can be included.

A similar approach introduced by Carter and Signorino (2010) also acknowledge that time-dummies may not be applicable in cases of binary dependent variable models and thus suggest the inclusion of polynomial time approximations. Their analysis entails a binary dependent variable in the case of a survival analysis in political science. As alternatives to parametric trend polynomials, they also propose semi-parametric modelling using splines. Carter and Signorino (2010) face a similar challenge as suggested in this paper. Their approach aims at explicitly modelling time within the context of their binary dependent variable indicating certain events. Against this backdrop, the event measured by the binary dependent variable cannot be distinguished from the underlying observed time units. Therefore time-dummy variables are not applicable in their context either. Thus, in this context, their approach is not concerned with the approximation of unobservable time fixed effects, but rather aims at explicitly modelling time in order to make statements about the likelihood and duration of an event. In applied time series econometrics parametric time trends are frequently used and discussed against the backdrop of potential spurious correlations and within the context of integration and co-integration of time-series. Here, deterministic time trends are implemented to model observed time trends and in the context of extrapolation and prediction models (Mills, 2003).

Application implementing linear time trends in the context of cartel overcharge estimations are Friederiszick and Röller (2010) as well as Hüscherlath et al. (2013). In these papers, the authors examine the effects of the cement cartel in Germany on cement prices. Implementing a linear trend in their models, the authors argue that many of the explanatory variables follow a linear time trend and may thus be more flexibly represented by a deterministic time trend polynomial of order one. Rather than a leaner data set, as put forward by the authors, the argument that the omitted variables may likely be highly correlated (macro)economic time series is probably valid. Their linear trend variable may indeed depict these observable as well as other unobservable developments underlying in the data.

The introduction of trend polynomials does not constitute an entirely novel approach in the empirical literature. The contribution of this paper however is the introduction of a parametric approach by means of trend polynomials as a standard tool for approximating time fixed effects. Thus, we provide an in-depth analysis of the properties of smoothing time fixed effects. Based on our analysis, we conclude, that smoothing time fixed effects should be introduced as means for obtaining time fixed effects when time-dummy variables are not available. Although in some settings, smoothing time fixed effects may only imperfectly approximate the underlying unobserved time-dependent effects, our results suggest that neglecting time fixed effects altogether typically results in higher bias.

We show that the polynomials of the time trend yield very similar results to time dummy variables in their mechanism and represent a smoothing of the discrete steps of time dummy variables. For this

reason, the more flexible standard approach using time dummy variables are superior to the trend polynomials in the context of continuous treatment variables. If it is not possible to include time dummy variables due to collinearities, smoothing time fixed effects are a reliable alternative under certain regulatory conditions.

2. Empirical Setting

The applied econometrician typically does not observe the full set of time-dependent variables underlying in longitudinal data and thus crucially relies on time fixed effects. The estimation equation is then of the form:

$$y_{it} = \beta_0 + \beta_1 x_{1it} + \beta_2 x_{2it} + \eta_{it}$$

$$\eta_{it} = \beta_3 x_{3t} + \varepsilon_{it}$$

in which $\eta_{it} = \beta_3 x_{3t} + \varepsilon_{it}$ is the empirical residual and ε_{it} is the error term. Hence, x_{3t} represents an unobservable omitted variable and thus leads to a bias if the variable of interest x_{1it} is correlated with x_{3t} . In this setting, x_{3t} only depends on time, such that a standard inclusion of time-dummy variables may sufficiently represent the underlying unobservable time-effects. The bias may thus be corrected by means of time-dummy variables in case applicable. The unobserved time-dependent variable x_{3t} represents numerous unobserved effects in real applications. Time-varying observed or unobserved effects in (micro-)economic applications are typically assigned to macro-economic developments. The underlying unobserved time-varying variables will however typically differ depending on the subject matter.

Smoothness of underlying time series

Many underlying macro-economic time series may be characterized as rather smoothly evolving over time, once seasonality has been controlled for.⁶ Smoothness of the underlying unobservable variables is a favorable property for smoothing time fixed effects. A readily available measure for smoothness is the lag one autocorrelation $\text{Corr}(x_{3t}, x_{3t-1})$. The higher the correlation the smoother is the time series. Table 1 shows the smoothness of time series from different fields of economic research. These macro-economic time series show an average smoothness factor of at least 0.61, but typically above

⁶ Note that in the typical setting, in which time-dummy variables result in biased estimates, seasonal dummy variables will still often be applicable. If the data frequency allows, seasonal dummy variables may further increase smoothness.

0.9. Even the typically very volatile time series for energy prices (here import prices for mineral oil & electricity price index) show a high smoothness factor.

Table 1: Smoothness of economic time series

Series	Smoothness	Min	Max	Mean	Sd	Length
Mineral oil ⁷	0.607	88.2	183.6	133.95	34.92	15
GDP ⁸	0.989	75.4	114.8	96.21	11.15	25
Unemployment ⁹	0.986	3	9.6	5.47	1.71	156
HCP1 ¹⁰	0.9978	75.7	105.5	89.74	9.64	24
PPI ¹¹	0.9621	83.03	104.18	94.30	7.62	19

Smoothness is characterized by the first lag correlation of the underlying unobserved time-series.

In order to introduce an intuitive approach to smoothing time fixed effects, we first postulate a number of properties for the unobserved time-dependent variable as well as the variable of interest. Before we relax these assumptions in the Monte Carlo simulations in section 3, we show results from Monte Carlo simulations conditional on the form of the curvilinearity of x_{3t} . For the matter of comparison between time-dummy variables and smoothing time fixed effects, we first show results from Monte Carlo simulations, in a setting in which both are applicable. Both are applicable in case the variable of interest is measured continuously. Subsequently we shall concentrate on the setting in which the variable of interest is merely measured binary, with a strict time division into event and control periods, where time-dummy variables are inapplicable. The postulated curvilinearity of the underlying unobservable time-series x_{3t} in this section can entail three different forms. We postulate three different intuitive forms, a linear time trend, a u-shaped or of a cubic form. Figure 1 shows the postulated courses.

Data generating process

With a time-range of $T = 20$ time-units, the data generating process further assumes that ε_{it} is normally distributed around 0 with a standard deviation of 10. The variable of interest x_{1it} is either simulated as a continuous (section 2.1) or a binary (section 2.2) variable. The additional explanatory variable x_{2it} is generated to be exogenous and normally distributed with a mean of 0 and a standard deviation of 10. The true coefficients are postulated as $\beta_0 = 10$, $\beta_1 = 15$, $\beta_2 = 2$ and β_3 lying randomly between 10 and 50 for the simulation with a continuous variable of interest x_{1it} (section 2.1) and between 0.5

⁷ Statistisches Bundesamt (2020), Index of import prices: GP09-061.

⁸ Eurostat (2020), GDP at market prices for the EU28, Index 2010=100.

⁹ Statistisches Bundesamt (2020), monthly unemployment rate (ILO-Concept): 13231-0003.

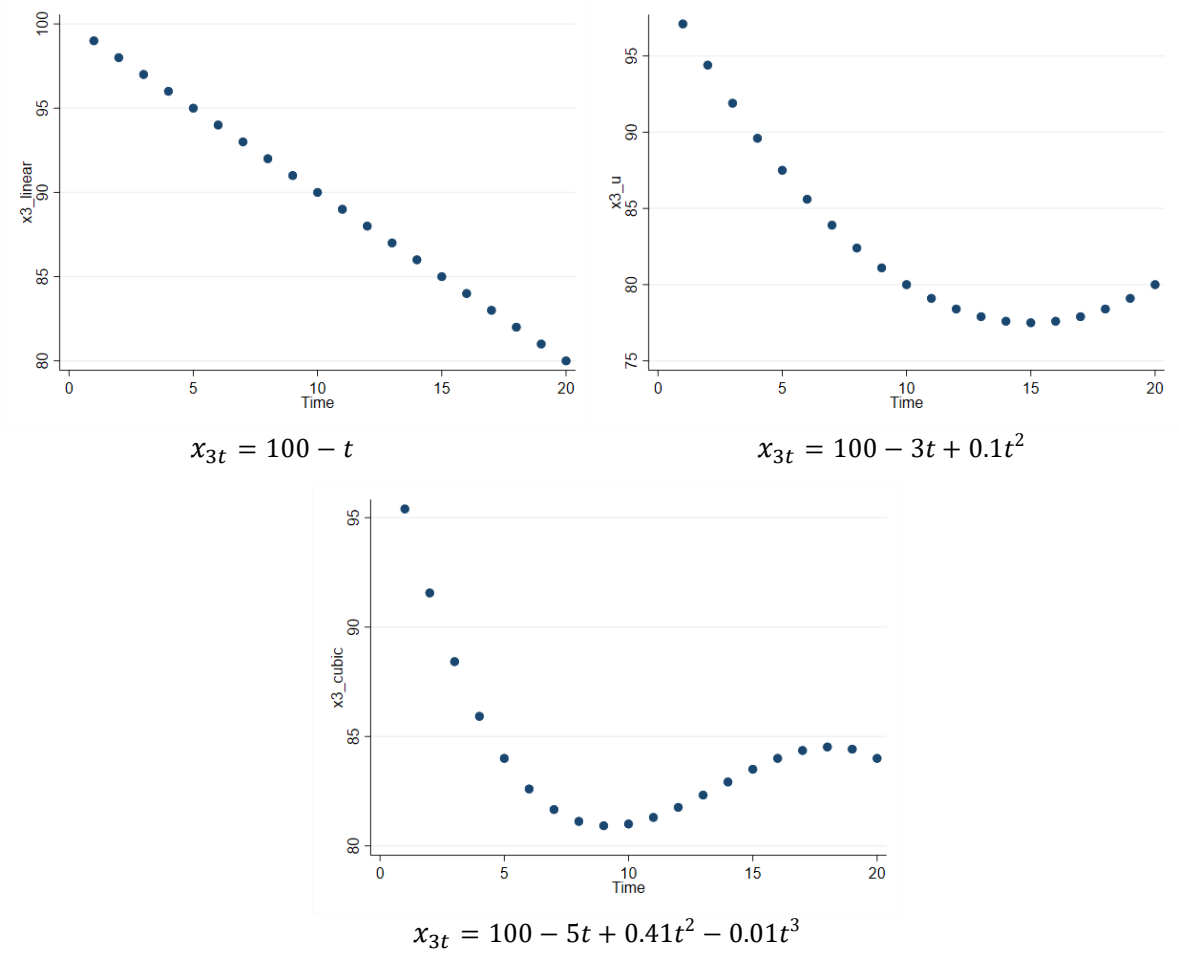
¹⁰ Eurostat (2020), Harmonized Consumer Price Index - Germany – yearly data, Index 2015=100.

¹¹ OECD (2020), Producer Price Index – EU28 – yearly data, Index 2015=100.

and 1 for the binary variable of interest x_{1it} (section 2.2).¹² The dependent variable is then simply the result of the generated (pseudo-)random variables and the postulated intensities of their effects.

For all simulations, the absolute correlation between the variable of interest x_{1it} and the unobservable x_{3t} is restricted to [0.3,1). This is done in order to postulate an initial bias if time fixed effects are not controlled for.¹³

Figure 1 Figures of three postulated forms of the unobserved time-dependent error



Three postulated forms for the unobserved underlying time-dependent error with the assumed respective underlying equations. First: linear. Second: quadratic. Third: cubic.

In order to obtain comparisons of approaches, different models are estimated on the basis of the randomly simulated data. Model 1 is the baseline model neglecting time-varying effects altogether.

¹² Since the relative influence of the error term on y increases drastically in the case of the binary treatment, the restriction on β_3 is conducted.

¹³ Note, the correlation may be negative or positive. A correction of bias by means of time fixed effects works irrespective of the direction of the correlation. A restriction to an absolute correlation therefore suffices.

Model 2 is nested in model 1 and includes T-1 time-dummy variables. Model 3 is nested in model 1 and uses smoothing time fixed effects, polynomials of the time trend with the power p up to P.¹⁴

$$\text{Modell 1: } y_{it} = \beta_0 + \beta_1 x_{1it} + \beta_2 x_{2it} + \eta_{it}$$

$$\text{Modell 2: } y_{it} = \beta_0 + \beta_1 x_{1it} + \beta_2 x_{2it} + \sum_{t=2}^{T-1} Year_t * \vartheta_t + \delta_{it}$$

$$\text{Modell 3: } y_{it} = \beta_0 + \beta_1 x_{1it} + \beta_2 x_{2it} + \sum_{p=1}^P Trend^p * \varphi_p + \mu_{it}$$

In the following, the simulations are carried out for a continuous (chapter 2.1) and a binary (chapter 2.2) variable of interest x_{1it} . The respective data generating process of x_{1it} is introduced in the respective chapter as well as simulation results.

Testing for the optimal order polynomial

As model 3 is nested in the baseline model 1, standard F-tests can be implemented to determine the optimal order polynomial. As it is readily available, we suggest a testing procedure using a F-tests in order to detect the optimal order of the polynomial for smoothing time fixed effects. The procedure entails testing for a sequential addition of trend polynomials starting from a trend polynomial of order one, as long as the F-statistic rejects the null hypothesis of no explanatory power of the added polynomial.

As smoothing time fixed effects imply a polynomial approximation of an unknown function and in practice clear-cut solutions might be rare from this condition alone, we suggest to impose two further restrictions to the test procedure. First, the additional polynomial should only be included if the t-statistics of all trend coefficients individually are significantly different from zero as well. If one of these conditions is not met for the additional polynomial, polynomials up to the last polynomial meeting both conditions should be used. Second, an exception from this rule should be the first order, linear polynomial as curvilinear errors must not necessarily follow a linear time trend. The curvilinear error might rather be stationary or even perfectly stationary. In such a case the first F-test on a merely linear time trend as well as the individual t-test will of course be insignificantly different from zero. Such a setting however does not necessarily imply that no curvilinearity is apparent. Therefore, we suggest that if one or both tests indicate insignificant results, the quadratic polynomial should be tested as well. In case, both the F-test on the quadratic polynomial is significant as well as the two individual t-

¹⁴ If model 3 is referred to in the following, a parametric regression model with polynomial approximation is always meant, regardless of the order of the polynomial. The order of the polynomial can range from 1 to T-2.

statistics of linear and quadratic polynomials, the procedure should start from there ignoring the mere linear trend.¹⁵

The testing procedure can be summarized as follows:

Include time trend polynomials of orders 1 to p in the model. Conduct the F-test for the p^{th} order polynomial and t-tests for order polynomials 1 to p . If all tests are significant repeat from the beginning, this time with order polynomials 1 to $(p+1)$. The optimal order polynomial is the last for which all tests are significantly different from zero.

The first order polynomial constitutes a special case: if the test procedure at stage 1 results in insignificant test-statistics, in any case also test for polynomials 2 to p and follow the above procedure.

In the simulations we also conduct this test procedure and report the results from automatically choosing the indicated optimal order of the polynomial derived from the tests. Results based on the choice the automatic decision concerning the order of the polynomial from the test procedure are labelled with the suffix “optimal” in the following sections.

2.1 Continuous Variable of Interest

In this subsection, a setting with a continuous variable of interest is assumed as in this setting both time-dummy variables and smoothing time fixed effects can be estimated allowing for a comparison of their respective properties. In practice, time dummy variables are standardly included in the regression in this setting. The following simulations are conducted three times, one for each of the three postulated forms of x_{3t} . The continuous variable of interest x_{1it} is generated using the Cholesky decomposition in order to postulate the desired correlation between η_{it} and x_{1it} . The generated random time series thus obtained serves as the basis of the data generating process of x_{1it} . x_{1it} is generated to be normally distributed around the time series x_{1t} with a standard deviation of 5

$$x_{1it} \sim N(x_{1t}, 5), t \text{ in } [1,20].$$

The Monte Carlo approach entails the simulation of 1,000 randomly generated data sets with the given properties. Table 2 shows the 95-%-confidence intervals of the estimated coefficients for each model and each postulated x_{3t} . An approach is considered consistent if it efficiently yields unbiased estimates. We consider an approach consistent if the postulated true value of the coefficient lies within

¹⁵ A significance level of $\alpha = 0.01$ for both F- and t-tests was used to conduct the presented simulations.

the 95-% confidence interval of the empirical distribution of estimated coefficients, based on estimating from a sufficiently large number of randomly generated data sets.

Table 2: 95-% Confidence intervals for the postulated shapes and each model

Estimated model	Postulated true form of error		
	(1) Linear x_{3t}	(2) U-Shaped x_{3t}	(3) Cubic x_{3t}
Model 1 – none	(20.2872; 20.6616)	(20.3189; 20.6995)	(18.2042; 18.4316)
Model 2 – dummy	(14.9990; 15.0022)	(14.9980; 15.0009)	(14.9991; 15.0021)
Model 3 – linear	(14.9995; 15.0009)	(16.3376; 16.5429)	(17.6132; 17.8166)
Model 3 – squared	(14.9995; 15.0010)	(14.9991; 15.0005)	(15.5565; 15.6604)
Model 3 – cubic	(14.9995; 15.0010)	(14.9990; 15.0005)	(14.9995; 15.0009)
Model 3 – optimal	(14.9995; 15.0010)	(14.9991; 15.0005)	(14.9996; 15.0009)

Continuous variable of interest: 95-% Confidence intervals of the empirical distribution of b_{1t} , the estimated coefficient for β_1 , from a Monte Carlo simulation entailing 1,000 randomly generated data sets.

In Table 2 the confidence intervals of the respective models indicated in column 1 are shown. The true postulated coefficient is $\beta_1 = 15$. The postulated shape of the error introduced in Figure 1 is indicated in row two of Table 2. The underlying true shape of the error in column (1) is linear, in column (2) the true curvilinear shape of the error is u-shaped and in column (3) the postulated true shape is cubic. The rows show results of each testing procedure. As introduced above, model 1 ignores time fixed effects altogether and model 2 controls for time fixed effects by means of dummy variables. Model 3 controls for time fixed effects using smoothing time fixed effects and is estimated with four different approaches. The three first specifications include only a linear trend (“model 3 – linear”), a linear and a quadratic trend (“model 3 – squared”), a linear as well as a quadratic and a cubic trend (“model 3 – cubic”). The last row shows results from the automatically chosen order of the polynomial based on the test procedure described above (“model 3 – optimal”).

As bias postulated in the empirical specifications throughout, model 1, in which time fixed effects are neglected altogether is biased disregarding the curvilinear form in the error. As time dummy variables are applicable when the variable of interest is continuous, model 2 is unbiased throughout. In the simple case with a postulated linear error as in columns (1), smoothing time fixed effects of order 1 is unbiased. The order polynomial of up to 3 remains unbiased. In case of postulated quadratic errors, unbiased estimates are obtained as of a quadratic trend polynomial. Similarly, in case of postulated cubic errors, the Monte Carlo simulations result in unbiased estimates as of a polynomial of order 3. Model 3 with automatically chosen order of the implemented polynomials based on the test procedure above yields consistent estimates.

The Monte Carlo simulations show that both time dummy variables as well as smoothing time fixed effects with the right order polynomial result in unbiased estimates. Smoothing time fixed effects yield consistent estimates and show to be reliable in case implemented correctly. Since the setting allows time dummy variables, these are however clearly favorable as they are not only consistent, but also more flexible and its implementation needs virtually no specific attention.

2.2 Binary Variable of Interest

In case the variable of interest is binary time-dummy variables are inapplicable. The binary variable of interest x_{1it} takes on a binary form

$$x_{1it} = \begin{cases} 1 & \text{if } t \leq 10 \\ 0 & \text{if } t > 10 \end{cases}$$

Although the setting is based on cartel overcharge estimations, the general results hold for other cases in which the variable of interest indicates events based on time. In this setting the variable of interest x_{1it} now splits the dataset in half. Correlations between x_{1it} and the unobserved x_{3t} will almost automatically arise since x_{1it} is immediately based on time and x_{3t} is likely to change over time. Since the relative effect of $\beta_1 * x_{1it}$ on y_{it} compared to the relative effect of $\beta_3 * x_{3t}$ on y_{it} is now much smaller compared to the continuous case, β_3 is restricted to values between 0.5 and 1.¹⁶ Again, the simulation was conducted using 1,000 repetitions.

As bias postulated in the empirical specifications throughout, model 1, in which time fixed effects are neglected altogether. As time dummy variables are not applicable when the variable of interest is discrete and indistinguishable from time-units, model 2 is biased throughout. In the simple case with a postulated linear error as in columns (1), smoothing time fixed effects of order 1 is unbiased. The order polynomial of up to 3 remains unbiased. In case of postulated quadratic errors, unbiased estimates are obtained as of a linear trend polynomial already. Due to the postulated rather flat u-shape in the simulation, a linear approximation of underlying time-dependent effects suffices to obtain unbiased estimates. In case of postulated cubic errors, the Monte Carlo simulations result in unbiased estimates as of a polynomial of order 3. Model 3 with automatically chosen order of the implemented polynomials based on the test procedure above yields consistent estimates throughout on average.

¹⁶ Before, the continuous x_{1it} had a mean of 100. Now it takes on the value 1 or 0. Hence, the relative effect of the error term containing $\beta_3 * x_{3t}$ on the variance of y_{it} would be much higher now and the resulting bias would therefore be extremely high. Therefore, the restriction on β_3 ensures comparability.

Table 3: 95-% Confidence intervals for the postulated shapes and each model

Estimated model	Postulated true form of error		
	(1) Linear x_{3t}	(2) U-Shaped x_{3t}	(3) Cubic x_{3t}
Model 1 – none	(22.4321; 22.6174)	(21.6925; 21.8646)	(16.8100; 16.8665)
Model 2 – dummy	(29.1247; 29.4824)	(27.7121; 28.0374)	(23.4334; 23.6579)
Model 3 – linear	(14.9627; 15.0251)	(14.9441; 15.0394)	(12.1302; 12.2429)
Model 3 – squared	(14.9626; 15.0250)	(14.9626; 15.0250)	(11.9095; 12.0074)
Model 3 – cubic	(14.9583; 15.0396)	(14.9583; 15.0386)	(14.9871; 15.0701)
Model 3 – optimal	(14.9624; 15.0248)	(14.9651; 15.0280)	(14.9869; 15.0699)

Binary variable of interest: 95-% Confidence intervals of the empirical distribution of b_1 , the estimated coefficient for β_1 , from a Monte Carlo simulation entailing 1,000 randomly generated data sets.

The Monte Carlo simulations show that time dummy variables are inconsistent in case the variable of interest is binary. Smoothing time fixed effects with the correct order polynomial reliably result in unbiased estimates in case implemented correctly. Implementing time dummy variables in such a setting is at least as harmful as neglecting time fixed effects altogether as is commonly done in the literature.

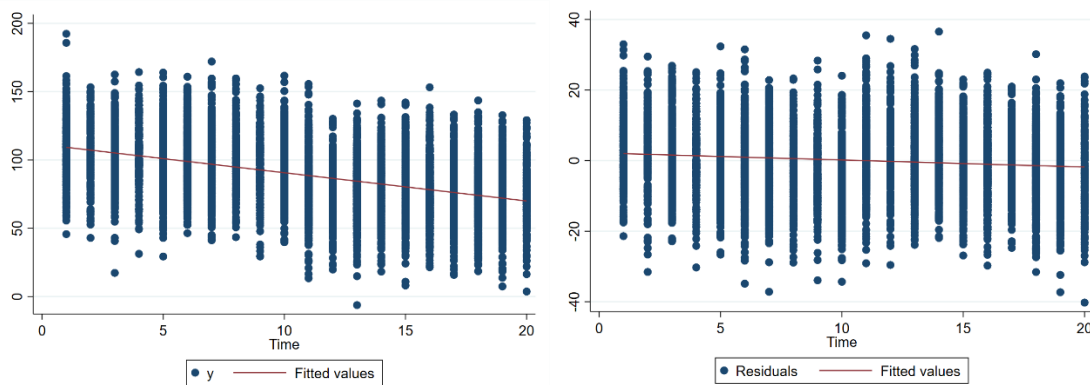
2.3 Graphical Analysis

For determining the order of the polynomial, a graphical analysis could be regarded as obvious approach since the dependent variable could in some cases already show a certain curvilinear form indicating a suitable order of the polynomial. Although this might be the case in some applications, a well-grounded economic analysis as well as a highly careful analysis of the empirical properties are inevitable.

In this section we show that often a graphical analysis of the curvilinearity of the dependent variable as well as the multivariate fitted residuals can give first insight about whether or not to include smoothing polynomials, and an indication of the order of the polynomial.

Figure 2 shows an example of the data generating process from section 2.2. The left hand panel shows the scatter plot for the dependent variable y_{it} . The scatter plot depicts the postulated linear time trend of the unobserved variable x_{3t} clearly in the dependent variable. Even the corresponding residuals plotted on the right panel show the linear trend. In this case, the scatter plots can give a good indication for an unobserved linear time series that will bias the binary variable of interest.

Figure 2: Linear error: Scatter plots



Linear error, binary variable of interest. Left panel shows scatter plot of dependent variable over time as well as bivariate regression line. Right hand panel shows fitted empirical residuals from a specification neglecting time fixed effects. Linear error graphically clearly visible.

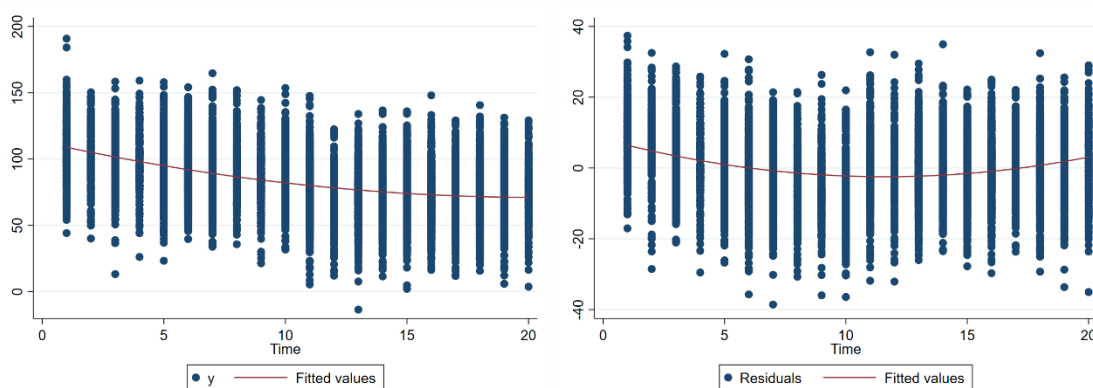
The example depicted in Figure 3 comes from the data generating process with postulated u-shaped x_{3t} . Again, the scatter plot of y_{it} against time shows the postulated u-shaped x_{3t} . The same is true for the scatter plot of the residuals from the model 1 neglecting time fixed effects.

However, in both cases the second graph might be misleading. While the scatter plot of y_{it} clearly indicates systematic differences over time, an analysis of the respective right panel scatter might guide the conclusion that there are no systematic time dependent differences. On the contrary, in both cases the OLS regression per construction attributes the unobserved time differences to the variable of interest.

However, analyzing the two scatter plots of a given specification can on the one hand give an indication on whether or not smoothing polynomials might be appropriate and on the other hand they can give first insights on an appropriate order of the underlying polynomial.

A sole graphical analysis is however by no means sufficient as such graphical analyses may not always give a clear indication as in the rather clear examples shown. In real world applications, a clear visually derivable potential curvilinear form is probably rare. In other words, solely relying on a graphical absence of clear (curvilinear) of systematic changes over time may considerably misguide in choosing a suitable specification.

Figure 3: Quadratic error. Scatter plots



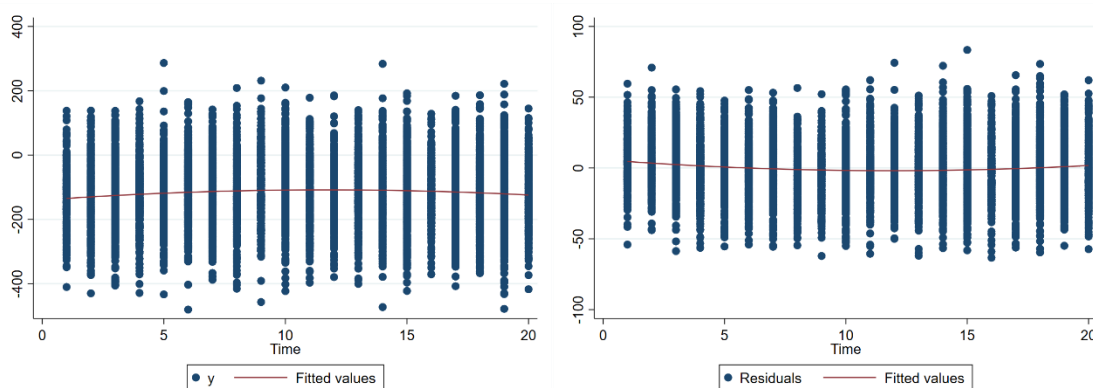
Quadratic error, binary variable of interest. Left panel shows scatter plot of dependent variable over time as well as bivariate regression line. Right hand panel shows fitted empirical residuals from a specification neglecting time fixed effects. U-shape graphically clearly visible.

Figure 4 again shows scatter plots for y_{it} and the residuals from model 1. The data generating process from chapter 2.2 has been modified for this example. First, an additional observable variable x_{4it} has been included. This variable is a random variable that is normally distributed around x_{3t} with a standard deviation of 10. The respective coefficient β_4 however equals $-1 * \beta_3$. In addition, the true error term ε_{it} now has a standard deviation of 20 instead of 10. This setting yields to a severely biased coefficient of $\beta_1 = 21.86$. However, due to the additional explanatory variable x_{4it} and an increased influence of ε_{it} , the scatter plots in Figure 4 cannot give any clear indication on whether or not to include smoothing polynomials and also not on the appropriate order of a polynomial. From the first scatter plot it can be seen that one might come to the conclusion that the unobserved variable might take on an inverted u-shape. The scatter plot of the multivariate residuals however, might give a hint on the u-shaped x_{3t} . By and large, the scatter plots almost indicate a linear relationship.

Nevertheless, graphical analyses should always be the first step in exploring for a model specification. As the minimal-examples however show, merely relying on a graphical inference is of course insufficient and may considerably misguide in real applications. Graphical analyses should always be crucially accompanied by economic rationale and formal testing.¹⁷

¹⁷ The testing procedure suggests implementing a quadratic polynomial, which is the true postulated curvilinearity in the error, and leads to an estimate of $\hat{\beta}_1 = 15.47$ with a given true parameter $\beta_1 = 15$.

Figure 4: Quadratic error: Scatter plots



Quadratic error, binary variable of interest. Left panel shows scatter plot of dependent variable over time as well as bivariate regression line. Right hand panel shows fitted empirical residuals from a specification neglecting time fixed effects. Postulated u-shape graphically almost flat.

3 Monte Carlo Simulations

In this section, results from more in-depth Monte Carlo simulations are shown. For this purpose, a modified data generating process compared to chapter 2 is used. The assumption of a clear curvilinear form of x_{3t} is now relaxed, such that the unobserved variable is generated randomly.

Although the main focus is on a binary variable of interest, the setting with a continuous variable of interest is addressed again as well. For the simulation in the setting with a continuous variable of interest, the Cholesky decomposition is crucial. The data generating process is in line with chapter 2.1. Nevertheless, in this case instead of postulating the curvilinear form of x_{3t} , both, x_{1it} and x_{3t} are generated by a Cholesky decomposition. Again, the mean of both, the variable of interest and the mean of x_{3t} equals 100 and the standard deviations are equal to 20. Again, the correlation is set to vary between 0.3 and 1.¹⁸ The simulated data sets cover 10 time periods. As before, all regression models are estimated using OLS.

In this standard setting the traditional time dummies are superior compared to the smoothing polynomials. Even though, the latter can also overcome the bias like already seen in chapter 2, the dispersion of estimated coefficients now is significantly larger. The mean squared error (MSE) for

¹⁸ This is true for both the correlation between the underlying time series generated by the Cholesky decomposition and the actual correlation between x_{1it} and x_{3t} . The latter might differ, since x_{1it} is generated to be distributed around an underlying time series generated by the Cholesky decomposition. The smoothness is restricted to values of at least 0.6.

model 1 equals 422.13, the MSE for model 3 using smoothing time fixed effects with polynomials of optimal order equals 52.54 and for model 2 with the time dummies the MSE is 0.001.¹⁹ This shows that even though a very large bias has been imposed by construction within the underlying simulation, the time dummies are not only unbiased but also efficient. Therefore, the time dummies are rightfully the standard tool of every econometrician for these kinds of settings. Since this is already well known our contribution to the literature is the use of smoothing time fixed effects in case time dummy variables are not available, only the latter setting will be discussed in more depth in this chapter.

Hence, a Monte Carlo simulation with binary variable of interest is carried out. The data generating process is closely linked to the data generating process in chapter 2.2. Time-series x_{3t} is generated in line with chapter 2.1 and has a mean of 100 and a standard deviation of 20. Variable x_{1it} takes on the following binary form:

$$x_{1it} = \begin{cases} 1 & \text{if } t \leq 5 \\ 0 & \text{if } t > 5 \end{cases}$$

The resulting data set spans over 10 time periods. In line with the simulation in chapter 2.2, β_3 is restricted to only vary between 0.5 and 1. Also, the correlation between the variable of interest x_{1it} and the unobservable x_{3t} is restricted to $[0.3, 1)$ in order to constitute bias by construction. The true coefficients $\beta_0 = 10$, $\beta_1 = 15$ and $\beta_2 = 2$ stay the same, so do x_{2it} and ε_{it} .

In the following, imposed restrictions on the Monte Carlo simulations will be gradually relaxed in order to analyze performance properties of smoothing time fixed effects. Our results show that the smoothness of the unobserved time series x_{3t} and the correlation between x_{1it} and x_{3t} play a considerable role in the performance of the smoothing time fixed effects.

Typically, economic time series are highly smooth over time. For the following analysis, the smoothness is measured by the lag-one autocorrelation:

$$\text{Corr}(x_{3t}, x_{3t-1}).$$

There are other measurements for smoothness, but the lag-one autocorrelation has the advantage that it allows easy statistical interpretation. A correlation close to one implies a smoothly varying time series, while a score around 0 implies that there is no overall linear relationship between one observation and the following. A score close to -1 on the other hand implies that the series regularly jumps around the mean in a very particular way. If one observation lies below the mean, the next one is likely to be above the mean by approximately the same amount.

¹⁹ The simulation has been conducted using 1,000 repetitions.

Smoothing time fixed effects under realistic regulatory conditions

Table 1 from section 2 shows different time series from different fields of economic research. It can be seen that the time series have on average a very high smoothness factor of more than 0.9 which also shows that typically no disruptive shocks occur. In order to analyze the properties of smoothing time fixed effects in a typical realistic setting, the Monte Carlo simulations are restricted such that the lag-one autocorrelation of the unobserved time series is larger than 0.7. Furthermore, extreme correlations between x_{1it} and x_{3t} larger than 0.9 are ignored. The results are summarized in Table 4.

Table 4: Results from Monte Carlo simulation with a realistic setting

	CI_l	CI_u	Mean	Sd	MSE
Model 1 – none	24.39	24.89	24.64	6.77	138.83
Model 2 – dummy	29.66	30.57	30.11	12.34	380.60
Model 3 – opt	14.82	15.33	15.08	6.97	48.64
Model 3 – min	14.84	15.06	14.95	3.02	9.15

Results from 2,839 data sets from the Monte Carlo simulation that are left after imposing the restrictions $\text{Corr}(x_{3t}, x_{3t-1}) > 0.7$ and $\text{Corr}(x_{1it}, x_{3t}) \in (0.3, 0.9)$. 95-% Confidence intervals are shown. CI_l shows the lower bound and CI_u reports the upper bound of the confidence interval.

It is obvious from the results that the bias of model 1 is severe since the regressions do not control for unobserved time changes altogether. The mean of the estimated coefficients is biased by 9.64. Due to the very setting with a discrete variable of interest, time dummy variables in model 2 cannot solve the bias due to perfect multicollinearity. The bias even increases under model 2. Smoothing time fixed effects yield unbiased estimates (model3 – opt). Their confidence intervals include the true coefficient, which takes the value 15. Here, “model 3 – opt” refers to the model for which the order of the polynomial has been chosen using the suggested testing procedure from chapter 2. “Model 3 – min” on the other hand refers to the theoretically perfect model, in which the polynomial has been chosen such that the bias of the estimated coefficient is minimal.²⁰ This of course is just a theoretical approach, but it allows to examine the performance of the smoothing time fixed effects separated from the performance of the suggested test. Table 4 shows that the suggested testing procedure yields unbiased estimates within this setting. Nevertheless, compared to “model 3 – min”, the standard error and hence the MSE are significantly higher.

²⁰ Unlike in a Monte Carlo simulation, in real applications the latter is of course never observable since the true parameter is unknown to the researcher.

Table 5: Results from Monte Carlo simulation with a realistic setting II

	CI_l	CI_u	Mean	Sd	MSE
Model 1	24.96	26.13	25.55	7.20	163.03
Model 2	31.42	33.44	32.34	12.48	459.38
Model 3 - opt	14.72	15.72	15.22	6.16	37.93
Model 3 - min	14.69	15.12	14.90	2.67	7.11

Results from 584 data sets from the Monte Carlo simulation that are left after imposing the restrictions $Corr(x_{3t}, x_{3t-1}) > 0.8$.

Table 5 shows another realistic setting in which the restrictions regarding the correlation between x_{1it} and x_{3t} is relaxed but the smoothness of x_{3t} is set to be higher than 0.8. Again, both “model 3 – min” and “model 3 – opt” deliver unbiased estimates. Due to the higher smoothness in turn, the dispersion of the estimated coefficients decreases.

Relaxing restrictions on smoothness

In order to further analyze the properties of smoothing time fixed effects, the so far imposed restrictions regarding the smoothness of x_{3t} are relaxed. The simulation now allows the smoothness parameter to vary between -1 and 1.²¹ Table 6 shows descriptive statistics for different smoothness values.

Table 6: Estimates depending on the smoothness of x_{3t}

Smoothness		(-1,0]	(0,0.2]	(0.2,0.4]	(0.4,0.6]	(0.6,0.8]
N		48,894	24,168	17,343	7,762	1,671
$Cor(x_{1it}, x_{3t})$		0.43	0.48	0.52	0.59	0.66
Model 1- none	Mean	20.96	21.64	22.18	23.10	24.15
	Sd	4.40	4.99	5.45	6.18	6.66
Model 3 – opt	Mean	23.66	20.50	18.71	17.03	15.95
	Sd	16.38	15.28	13.67	11.85	9.06
Model 3– min	Mean	19.21	17.57	16.65	15.90	15.33
	Sd	8.34	7.63	6.52	5.30	3.94

Results from a Monte Carlo simulation with 100,000 randomly generated data sets and the restriction $Cor(x_{1it}, x_{3t}) > 0.3$. We refrain from showing results from time dummy variables as they are extremely biased and thus can be regarded as inapplicable due to the underlying setting.

²¹ The correlation between x_{1it} and x_{3t} is still restricted to only vary between 0.3 and 0.9.

From Table 6 follows that the performance of smoothing time fixed effects crucially depends on the smoothness of the unobserved time series. Both specifications of model 3 result in less bias and less variance of the estimated coefficients the larger the smoothness parameter. Both smoothing time fixed effects with optimal order polynomial as well as minimal bias approximate the true parameter $\beta_1 = 15$ increasingly well the smoother the underlying bias becomes. In line with Table 4 both the expected value and the standard deviation for the models with tested order of polynomials is strictly larger compared to the model with minimal bias.²²

Furthermore, the correlation between x_{1it} and x_{3t} per construction increases if the smoothness of the unobserved time series x_{3t} increases. Since x_{1it} is a binary variable based on time, a smoother x_{3t} will yield a larger correlation. In order to obtain an initial bias in the first place, all cases in which x_{3t} does not or only changes slightly over time are eliminated. However, due to increased smoothness, bias correcting properties of smoothing time fixed effects overweigh the additional initial bias stemming from increased correlation.

Relaxing restrictions on correlations

Regarding correlations, so far only the correlation between x_{1it} and x_{3t} have been shown. However, correlations between the unobserved variable x_{3t} and the dependent variable x_{1it} as well as y_{it} also play a crucial role for unbiased estimations of β_1 . Table 7 gives an overview of the means of the estimated coefficient for different combinations of correlations $\text{Corr}(x_{1it}, x_{3t})$ and $\text{Corr}(y_{it}, x_{3t})$. With regard to the correlation between x_{1it} and x_{3t} it can be seen that a small correlation typically results in an overcorrection of the otherwise overestimation due to omitted variables bias that would arise from model 1, within a certain range of values for $\text{Corr}(y_{it}, x_{3t})$.²³ A high correlation between x_{1it} and x_{3t} on the other hand results in downwards corrected coefficients compared to model 1, still entailing a positive bias of the estimated coefficients. These two effects overlap each other. While a higher correlation leads to a higher omitted variables bias, which has to be overcome by time fixed effects, for a low correlation between x_{1it} and x_{3t} the bias is less pronounced and hence smoothing time fixed effects consume too much of the variance of y_{it} . Hence the effect of x_{1it} is underestimated and the original bias overcorrected. The correlation between y_{1it} and x_{3t} on the other hand does not influence the direction but rather the intensity of the bias. For higher degrees of smoothness, for

²² For either model, the confidence interval never includes the true coefficient $\beta_1 = 15$. For the last column, the CI for the model with tested order of the polynomial approximation equals [15.51,16.38] and for the optimal polynomial [15.14,15.52].

²³ Model 1 estimates a $\hat{\beta}_1 = 23.46$ for which both correlations are in the range of [0.3,0.65).

example at least of 0.8, all results shown in Table 7 will improve overall.

Table 7: Mean and standard deviation of estimated coefficients depending on $\text{Corr}(x_{1it}, x_{3t})$ and $\text{Corr}(y_{it}, x_{3t})$.

		$\text{Corr}(y_{it}, x_{3t})$		
		[0.3,0.65]	[0.65,1]	[0,1]
$\text{Corr}(x_{1it}, x_{3t})$	[0.3,0.65]	14.13 (4.00)	12.91 (9.71)	14.24 (3.91)
	[0.65,1]	16.07 (3.46)	17.90 (8.17)	16.11 (3.95)
	Overall: [0.3,1]	15.42 (3.76)	16.69 (8.82)	15.40 (4.04)

Monte Carlo simulation with 10,000 randomly generated data sets. Standard deviation in parentheses. Restriction to smoothness $\text{Corr}(x_{3t}, x_{3t-1}) > 0.6$. True parameter is $\beta_1 = 15$.

4. Discussion

In this section we discuss the simulation results as well as the test procedure and implications of smoothing time fixed effects. Furthermore, we address selected related topics in the given context.

Results from the Monte Carlo simulation

Table 8 summarizes the results from the Monte Carlo simulations. For different combinations of correlations, the bounds of the confidence intervals of the estimated coefficients are shown, as well as the frequency of the randomly generated data sets left after imposing the respective restrictions. In addition, the results are presented separated by degrees of smoothness. Again, “Model 3 – opt” refers to the smoothing time fixed effects following the suggested testing procedure. “Model 3 – min” refers to the model where the order of the polynomial is chosen in terms of minimal error between the estimated and the true coefficient.

It can be seen that smoothing time fixed effects can best approximate smooth changes in the unobserved variables. However, erratic changes and extreme shocks can be correctly controlled for up to a certain extent. A higher degree of smoothness leads to overall unbiased estimates, while a lower degree of smoothness can only partly correct the bias. For the simulations with a smoothness of the unobserved variable x_{3t} that is larger than 0.8, only the estimated coefficients for simulated data sets with both $\text{Corr}(y_{it}, x_{3t})$ and $\text{Corr}(x_{1it}, x_{3t})$ smaller 0.65 but higher 0.3 are biased (see Table 8). In addition, the estimates for $\text{Corr}(y_{it}, x_{3t}) > 0.65$ and small $\text{Corr}(x_{1it}, x_{3t})$ are only somewhat

reliable, since only 4 simulated data sets remain after imposing the restriction. All in all, the smoothness of the unobservable x_{3t} has a positive effect on the estimations using smoothing time fixed effects. Both, the overall bias and the dispersion of the estimated coefficients significantly decrease.

With regard to the correlation between y_{it} and x_{3t} it can be seen that a higher correlation will enlarge the overall bias. This is very intuitive since this corresponds to a higher influence of the error term on the variance of y_{it} . The larger the influence, the larger the omitted variables bias will be.

While the smoothness of x_{3t} and the correlation between y_{it} and x_{3t} only impact the magnitude of the bias, the correlation between x_{1it} and x_{3t} on the other hand influences the direction of the bias. For small values of $\text{Corr}(x_{1it}, x_{3t})$ the model with smoothing time fixed effects leads to an overcorrection of the initial bias. For large values of $\text{Corr}(x_{1it}, x_{3t})$ the initial omitted variable bias from model 1 becomes very high.²⁴ In this case, smoothing time fixed effects cannot fully correct the bias, such that a portion of the bias remains. Therefore, there is a trade-off. Two opposing forces that are related to the correlation between x_{1it} and x_{3t} influence the direction of the remaining bias. While a higher correlation enlarges the initial bias that smoothing time fixed effects have to correct, small values of $\text{Corr}(x_{1it}, x_{3t})$ might lead to some kind of overfitting. The initially already relatively small bias will be typically approximated by multiple trend polynomial variables within the regression. These polynomials might lead to an overfit, that absorb more of the variation of y_{it} than optimal. In this case, part of the effect of the variable of interested is absorbed by the approximation. This problem is more pronounced if the smoothness parameter of x_{3t} is small. In this case, the polynomial approximation using smoothing time fixed effects is more difficult to achieve compared to an approximation of a very smooth x_{3t} .

Table 8: Summary of Monte Carlo findings.

		Smoothness>0.6			Smoothness>0.8		
$\text{Corr}(y_{it}, x_{3t})$	$\text{Corr}(x_{1it}, x_{3t})$	Model 3 - opt	Model 3 - min	N	Model 3 - opt	Model 3 - min	N
$\in (0.3, 0.65]$	<0.65	(11.95;12.64)	(13.98;14.29)	2,530	(11.43;13.71)	(13.40;14.63)	71
	>0.65	(17.73;18.14)	(15.98;16.17)	5,013	(15.08;16.13)	(14.83;15.31)	402
$\in (0.65, 0.1)$	<0.65	(6.11;11.91)	(11.43;14.40)	164	(5.93;17.22)	(11.59;15.92)	4
	>0.65	(20.05;23.06)	(17.19;18.60)	514	(13.23;21.38)	(13.46;16.57)	43

Summary of the results from the Monte Carlo simulations on smoothing time fixed effects.95-% confidence intervals for several combinations of ranges for correlations as well as smoothness parameters are shown.

²⁴ For model 2, there is a clear positive relationship between $\text{Corr}(x_{1it}, x_{3t})$ and the bias. If $\text{Corr}(x_{1it}, x_{3t}) > 0$ the bias will be strictly larger than 0. The higher $\text{Corr}(x_{1it}, x_{3t})$, the larger the positive bias.

Regarding the suggested testing procedure, the results from both chapter 2 and 3 show, that the resulting regression is unbiased under certain regulatory conditions. However, chapter 3 also introduces “model 3-min” in which the order of the polynomials has been chosen to minimize the resulting bias (which in real application are unknown to the researcher). It can be seen that the testing procedure is not optimal in all ranges of possible values for smoothness and correlations, yet. While the bias for this model is rather small as well, the dispersion is rather high compared to “model 3-min”. However, as seen in Table 4 from chapter 2 the testing procedure leads to unbiased estimates for realistic settings.

Related topics

As the binary variable of interest divides time in two periods of event and control, systematic differences over time are likely to occur, potentially accompanied by a considerable correlation with the error term. Hence a bias due to the omission of time fixed effects is very likely to be present from the very setting. Against this backdrop, autocorrelated error terms extensively discussed in time series econometrics appear as closely related. If there are systematic differences between event and control periods, the error terms are likely to be autocorrelated. Hence, autocorrelation of the error terms tend to signal the presence of bias a bias that are likely to be solvable by time fixed effects.

In this context we would like to refer to the literature on autocorrelation (serial correlation), stationarity, (co-)integration and spurious correlations. These phenomena are extensively addressed in time series econometrics. We show that these problems can be related to the problem of an omitted variables bias in the given setting. The phenomenon of spurious correlations is typically introduced in a similar way as it is presented in this paper and can be described as a special case in which the true β_1 equals 0. The omitted variable is a confounding factor that is common for both time series. The omitted variable is therefore serially correlated over time. Nevertheless, since smoothing time fixed effects can constitute a crucial remedy for unobserved time dependent changes of the error term.

Lastly, we would like to discuss further frequent estimation techniques within similar contexts. In a setting entailing omitted variable bias, especially instrumental variable regressions are put forwards when dealing with the present endogeneity. In the given setting however, traditional instruments may usually not be applicable however, if at all, since an instrument has to meet both validity and relevance.²⁵ A valid instrument in turn has to depict the time changes of the variable of interest. This

²⁵ A valid instrument has to meet two conditions. First, it has to be correlated with the variable of interest, hence be relevant. Second, it has to be uncorrelated to the omitted variable, hence be exogenous.

however may imply that a potential instrument is not exogenous since it may still be correlated to unobservable variables in the error term. Against this backdrop, the relevance of smoothing time fixed effects becomes even more pronounced, especially since smoothing time fixed effects themselves do not introduce additional bias.

The easy and readily available implementation of parametrically modelled smoothing time fixed effects makes the suggested procedure highly appealing. Since it is applicable for parametric models estimated by OLS, it is easier and more straightforward to implement compared to potential alternative approaches such as semi-parametric estimators.

5. Conclusion

For longitudinal data time dummies are the standard method to control for unobserved time depending effects. However, if the variable of interest depends on time and takes on a binary form, these are typically no longer applicable due to multicollinearity issues.

Although in this setting, the variable of interest is likely to be biased, the literature typically ignores the bias altogether, potentially due to a lack of a consistent approach to control for time fixed effects in this context. Our paper contributes to the literature as we introduce a simple and readily available parametric approach to control for time fixed effects in case time dummy variables are typically inapplicable. Although in some settings, smoothing time fixed effects may only imperfectly approximate the underlying unobserved time-dependent effects, our results suggest that neglecting time fixed effects altogether typically results in higher bias.

We show that smoothing time fixed effects can mitigate and under certain regulatory conditions even eliminate the bias caused by omitted variables in this setting. The smoother the unobserved variable is, the less biased and dispersed the estimated coefficients are. We have shown that economic time series typically smoothly evolve over time. Under this assumption, we show that under smoothing time fixed effects unbiased estimates can be obtained. As the introduced approach implies testing nested hypotheses, a standard testing procedure enables the identification of the order of the trend polynomial. We show that this procedure works well under certain regulatory conditions, that we consider as highly realistic.

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