—ONLINE APPENDIX— How Britain Unified Germany: Trade Routes and the Formation of the Zollverein

Theoretical Framework

In this section, we formalize the ideas from the main text. To this end, we make several (strong) assumptions. We start with the assumption that each state can be modeled as one revenue-maximizing agent, based on our reading of the historical situation after 1815. Moreover, we focus on colonial imports and assume that all trade originates from exogenous world supply, with exogenous f.o.b. prices at the source. Given the importance of colonial goods for tariff revenue at the time, we think this is justifiable. Our focus is on the effect of geographic location on optimal tariff policy, including the possibility of forming a custom union with other states. We first consider the behavior of a single revenue-maximizing state, as in Irwin (1998), then add a second state to model revenues from transit trade and relative geography, add third states to capture competition over transit trade, and finally examine the conditions under which states have an incentive to form a customs union.

One State

Our starting point is Irwin (1998): consider a small state i that observes a linear demand for an imported good $M_i \geq 0$ as

$$M_i = D_i - ap_i, \tag{1}$$

where $D_i > 0$ stands for the size of the market in i, and $a > 0$ is the elasticity of demand w.r.t. price at location i, $p_i > 0$. Extending Irwin (1998), we decompose this price into three components: The price at the source location (a given p_w), the physical transport costs, and the political costs involved in trading the good to i. We assume that transport costs are an outcome of competitive and well-informed traders that constantly search for the least-cost path from w to i. Transportation of the good from w to i implies a positive per-unit cost $cost_{wi}$, assumed to be independent of p_w (specific). This yields

$$p_i = p_w + \min_{r \in W_{wi}} (cost_r). \tag{2}$$

We assume that physical costs $\phi > 0$ are exogenous and non-negative.[1] The focus of the model is on the political trade costs t_i, which are costs associated with crossing of any border of state i and are endogenous to the framework. For a least-cost route that travels through a set of states $r = (r_1, .., r_{|r|})$, the costs of any route r in W_{ij} is the sum of all physical and political costs,[2]

$$r \in W_{ij} \Rightarrow r_1 = i \text{ and } r_{|r|} = j \qquad cost_r = \sum_{n=2}^{|r|} \left(\phi_{r_{(n-1)} r_n} + t_{r_n} \right).^3 \tag{3}$$

What about the political trade costs t_i? With one single state, the state behaves as if located on an island, directly trading with an outer world, given exogenous source prices and physical trade costs. In fact, this is the standard assumption in nearly all trade models: that we can ignore potential transits via other states. In this "island case" the tariff t_i that maximizes revenues R is:

$$R_i^I = \max_{t_i^I} \left(t_i^I M_i \left(t_i^I \right) \right). \tag{4}$$

Hence, following Irwin (1998), the state sets t_{ig}^I (the"island tariff") to the value retrieved by inserting Equations 1 – 3 into Equation 4, and taking the first derivative w.r.t the tariff rate,

$$\frac{\partial \left[t_i^I \left(D_i - a \left(p_w + \phi_{wi} + t_i^I \right) \right) \right]}{\partial t_i^I} = 0 \Leftrightarrow t_i^I = \frac{D_i - a \left(p_w + \phi_{wi} \right)}{2a}. \tag{5}$$

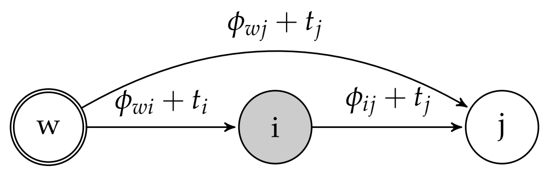


Figure A.1: *Two states and the world. If the direct edge from w to j is more costly than via i, i gains potential revenue. If the path wj would be absent, j would be an enclave of i.*

Two States

Once we introduce a second state (Equation A.1), tariffs and revenue now depend on the extent to which their least cost paths cross, hence on their geographical location. Consider the extreme case that all imports to the second state j have to pass via i. As argued above, states did generally tax not only imports but also transits. With this, the optimization problem implies multiple marginalization (see Church and Ware (2000)). State j knows that its consumers will have to bear this tariff, and sets the optimal tariff solving for (analogously to Equation 5), while anticipating j's reaction tariff (see Proposition 1 for details) to

$$\left[t_i^j \mid \phi_{wj} \to \infty\right] = \frac{\frac{2}{3}D_i + \frac{1}{3}D_j - a\left(p_w + \phi_{wi} + \frac{1}{3}\phi_{ij}\right)}{2a}. \tag{6}$$

If we now compare this tariff with the island tariff from Equation 5, we see that the resulting tariff can be higher—but also lower than the island tariff—depending on the relative size of the states, and the transport costs ϕ_{ij}. The larger D_j is relative to D_i, the higher the tariff t_i^j compared to the island tariff. Intuitively, state i can now generate additional revenue by taxing consumers in j. But to what extent?

The Trade-off of an Upstream State

Consider Figure 3 from our article, which shows the case that tradesmen can avoid paying t_i by using a detour. Formally, we define the difference between the least-cost path that transits a set of states and the least-cost path that detours the same set of states ($\{i\}$ in our case), as

[1]They need not to be symmetric, so that $\phi_{wi} \not\equiv \phi_{iw}$, in other words the costs of trading on a river depends on the floating direction. We will later rely on a GIS least-cost path algorithm to estimate these physical costs.

[2]r_1 is always i, and ruling out smuggling (There cannot be any route around the border of the destination state) yields $r_{|r|} = j$.

$$h^{j}_{\{i\}} = \min_{r \in W_{wj}, \{i\} \not\subset r} \left(\sum_{n=2}^{|r|} \left(\phi_{r_{(n-1)} r_n} \right) \right) - \min_{r \in W_{wj}, \{i\} \cap r} \left(\sum_{n=2}^{|r|} \left(\phi_{r_{(n-1)} r_n} \right) \right) > 0 \tag{7}$$

This yields

$$h^{j}_{\{i\}} = \phi_{wj} - \left(\phi_{wi} + \phi_{ij} \right) > 0.$$

Let i be the state that is located "upstream" (which in our historical case would mean a state *closer* to the sea as the source of colonial goods). As we see from Figure 3 in our article, the revenue of i is discontinuous at $h^{j}_{\{i\}}$. Any higher tariff implies the loss of transit trade to j. To account for whether there is transit destined to j, i will consider $d_{ijg} \in \{0, 1\}$ to compare the revenue from setting $t_{ig} \leq h^{j}_{\{i\}}$ (which would allow imports from j to transit i, $d_{ijg} = 1$) with the maximal revenue from setting t_{ig}, a tariff above $h^{j}_{\{i\}}$ which forces traders to detour i ($d_{ijg} = 0$). The problem of i is therefore given by

$$R_i = \max_{t_i, d_{ij} \in \{0,1\}} \left(t_i (M_i \left(t_i \right) + d_{ij} M_j \left(t_i \right)) \right) \qquad \text{s.t. } d_{ij} t_i \leq h^{j}_{\{i\}}. \tag{8}$$

This yields:

Proposition 1. *For an upstream state, there is a trade-off between tariff revenue from imports and tariff revenue from transits.*

Proof. Given j is solving for its optimal tariff anticipating t_i, it sets up

$$\frac{\partial \left[t_j \left(D_j - a \left(p_w + \phi_{wi} + t_i + \phi_{ij} + t_j \right) \right) \right]}{\partial t_j} = 0 \Leftrightarrow t_j = \frac{D_j - a \left(p_w + \phi_{wi} + t_i + \phi_{ij} \right)}{2a} \tag{9}$$

Country i would take transits to j into account, t^{j}_{i} by setting up its revenue function's first derivative w.r.t t^{j}_{i},

$$\frac{\partial\left[t_i^j\left(D_i - a\left(p_w + \phi_{wi} + t_i^j\right) + D_j - a\left(p_w + \phi_{wi} + t_i^j + \phi_{ij} + t_j\right)\right)\right]}{\partial t_i^j} = 0, \tag{10}$$

replacing t_j from Equation 9, and set its own tariff such that

$$\left[t_i^j \mid \phi_{wj} \to \infty\right] = \frac{\frac{2}{3}D_i + \frac{1}{3}D_j - a\left(p_w + \phi_{wi} + \frac{1}{3}\phi_{ij}\right)}{2a}. \tag{11}$$

□

Proposition 2. *Countries may have to give up revenue from transit trade when setting the island-tariff*

Proof. If country i forfeits transit trade to j, the tariff rate t_i is retrieved as in the island case, $t_i = t_i^I$. Consider the tariff that country i can set allowing for transit trade to j, t_i^j. The condition $d_{ij}t_i \leq h_{\{i\}}^j$ can be either binding or non-binding, and $t_i^j \leq h_{\{i\}}^j$. Consider the case that the condition is non-binding, for example $h_{\{i\}}^j \to \infty$. Country i would only find this beneficial iff

$$t_{ig}^j\left(M_i\left(t_i^j\right) + M_j\left(t_i^j\right)\right) \geq t_i^I\left(M_i\left(t_i^I\right)\right) \tag{12}$$

Consider the case in which this tariff would be too high to allow for transit. If country i wants to allow transit from j, it has to set $h_{\{i\}}^j$. Otherwise, if this tariff is lower than the detour costs anyway, country i can set the tariff as in the surrounded case,

$$t_i^j = \begin{cases} [t_i^j \mid h_{\{i\}}^j \to \infty] & \text{if } [t_i^j \mid \phi_w \to \infty] \leq h_{\{i\}}^j \\ h_{\{i\}}^j & \text{else} \end{cases} \tag{13}$$

Monotonicity of demand for each of the countries' w.r.t. tariffs imposes that this is optimal. The binary decision of allowing for transits to j is therefore expressed as

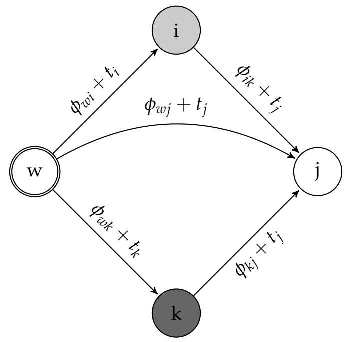


Figure A.2: *Given that the direct route from w to j is very expensive, i and k compete over transits. If i and k could agree on a single tariff rate (for example by sharing the revenue), this competition can be avoided.*

$$d_{ij} = \begin{cases} 1 & \text{if } t_i^j \left(M_i \left(t_i^j \right) + M_j \left(t_i^j \right) \right) \geq t_i^I \left(M_i \left(t_i^I \right) \right) \\ 0 & \text{else} \end{cases} \tag{14}$$

□

Competition Between two Upstream States

Next, we allow a third state k to compete with i over the transit trade destined for j, as in Figure A.2. There are three routes to j, $W_{wj} = \{(w, j), (w, i, j), (w, k, j)\}$. Assume that the cheapest route goes via i, the second cheapest route via k, and the most expensive route is crossing neither i nor k. The cheapest route to j therefore depends on the sum of trade costs: the exogenous physical costs and the endogenous tariffs,

$$min(cost_{wk}) = \begin{cases} \phi_{wi} + \phi_{ij} + t_i + t_j & \text{(cheapest route via i)} \\ \phi_{wi} + \phi_{ij} + h^j_{\{i\}} + t_k + t_j & \text{(second cheapest, detour i, via k)} \\ \phi_{wi} + \phi_{ij} + h^j_{\{i,k\}} + t_j & \text{(detour both i and j)} \end{cases} . \tag{15}$$

This yields

Proposition 3. *Two states can engage in Bertrand competition over the least cost routes between world markets and a third state. The question whether any state will find it beneficial to engage in*

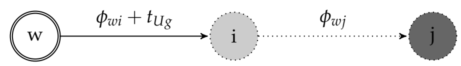


Figure A.3: *A potential customs union between i and j would eliminate tariffs between i and j*

competition depends on their relative size and geographic location.

Proof. Consider the case that D_k is sufficiently large and transport costs ϕ_{ij} and ϕ_{kj} are sufficiently low, so that both i and k would find it beneficial to allow for transit trade to j. As long as t_i is below $h^j_{\{i\}}$, country k would have to set a negative tariff rate (which cannot be revenue-maximizing). Additionally, country i can safely increase its tariff above the level of $h^j_{\{i\}}$ to the point it expects k to lower its tariff rate to attract the transit. The maximization is given by

$$R_{ig} = \max_{t_i, d_{ik} \in \{0,1\}} \left(t^j_i (M_i \left(t^j_i\right) + d_{ij} M_j \left(t^j_i\right))\right) \text{ s.t. } d_{ij} t^j_i \leq h_{\{i\}} + t^j_k \tag{16}$$

while i has to be aware that j will decrease its tariff rate below the island tariff to attract transit if this comes with a positive revenue effect, so that

$$t_j = \begin{cases} t^I_j & \text{if } \left(t_i - h^k_{\{i\}}\right)\left(M_j\left(t_i - h^k_{\{i\}}\right) + M_k\left(t_i - h^k_{\{i\}}\right)\right) < M_j\left(t^I_j\right) \\ \left(t_i - h^k_{\{i\}}\right) & \text{else} \end{cases} \tag{17}$$

which in turn means that i can safely raise its tariff until it expects k to be indifferent between $R_k\left(t^I_k\right)$ and $R_k\left(t^j_k\right)$. □

Customs Unions

The above formulation (assuming more than three players) captures the situation in which all states maximize separately. It explains how the sum of tariffs paid for by consumers in remote (downstream) states may be prohibitively high, and overall demand low. A possible solution would be to maximize tariff revenues cooperatively: in the form of a customs union. We define a customs union as a set of states (U) that agree on a common external tariff rate (for imports and transits, t_U), eliminate all tariffs between each other, and distribute the revenues so that any member i would receive a share π^u_i of R_U.[4]

[4]See Viner (1950). For simplicity, we assume that the rules of these unions are given, and non-negotiable.

State i from figure A.3 faces yet another binary decision γ_i^u. Should it maximize tariff revenue separately, or join a customs union to receive share Π_{iU}?

$$\max_{\gamma_i^u \in \{0,1\}} \left(\left(1 - \gamma_i^u\right) R_i + \gamma_i^u \pi_i^U R_u \right) \tag{18}$$

Benefits of a Customs Union

From the above formulation, it follows that geography conditions the foundation of a customs union. Only if the union creates revenues otherwise wasted due to multiple marginalization would states give up their independent maximization,

Proposition 4. *The decision of any state to join a customs union depends on the geographic location and size of the state, compared to the geographic location and size of the customs union.*

Proof. We have to show under which conditions the sum of independent revenues is smaller than the revenues of the customs union,

$$R_U - \left(R_i + R_j\right) \geq 0.$$

Regarding the customs union, we retrieve the tariff charged analogous to the independent maximization,

$$t_u = \frac{D_i - a\left(p_w + \phi_{wi}\right) + D_j - a\left(p_w + \phi_{wi} + \phi_{ij}\right)}{4a}. \tag{19}$$

Import volume M_u can then be calculated by solving Equations 1–3 in reverse order. Multiplying this volume with t_u as in equation 4, yields the union's revenues R_u. We set up the revenue function of independent j by inserting Equation 6 into Equation 9 to retrieve t_j, solve for M_j from equations 1–3 (as pictured in figure A.1), and insert t_{ig}^j and M_j into equation 4. This yields optimal t_j, the resulting imports M_j, and finally R_j. Revenue R_i can then be calculated by inserting the tariff from 6, transit M_j, and imports M_i (from Equations 1–3 reversely) into the revenue Equation 8.

To understand the effect of relative size (relative demand), we express D_j in terms of D_i. This yields $D_j = D_i - \delta$, while $\delta \lesseqgtr 0$ is just the difference, so that δ can proxy relative size.

Replace $D_i - \delta$, and consider first and second derivatives of the customs union effect w.r.t. δ. This shows that the relationship between the customs union effect and the relative size is convex. With increasing inequality in sizes, the customs union effect becomes positive.

Focus on the effect of physical transport costs, in absolute and relative terms. Assume a negative shock on the absolute level of physical transport cost, for example through technological progress. Replace ϕ_{wi} by $\phi_{wi} - \tau$, and ϕ_{ij} by $\phi_{ij} - \tau$. First and second derivative w.r.t. τ reveal a convex link.

The first and second derivatives of the customs union effect w.r.t. ϕ_{ij} yield a concave function. The effect is smallest at either extremely low or extremely high costs ϕ_{ij}. Consider the extreme case of no physical transport costs, then there would be no gain from cooperation. As physical transport costs approach infinity, shortest paths and detours converge in relative terms. □

Negative Effects of a Customs Union for an Upstream State

States such as the free cities of Hamburg and Bremen, Germany's trade entrepôts remained outside of the German customs union until 1888, even after the foundation of the German empire in 1871. The primary reason is that revenues within the German customs union were distributed relative to population shares. For states such as Hamburg with a beneficial geographic position, joining the German customs union would have resulted in a loss of revenue.

Proposition 5. *A state can lose out from joining a customs union, depending on it geographic location and the agreed share in joint revenues.*

Proof. Assuming a customs union $u = \{i, j\}$ would distribute revenues as follows

$$\pi_i^u = \frac{D_i}{D_i + D_j}. \tag{20}$$

Compare figures A.1 and A.3. Consider the case in which state i has a strong geographic advantage over j, so that $h_{\{i\}} > t_{ig}^j$ (Equations 12 and 6). When deciding whether to join the union, i faces the trade-off (Equation 18),

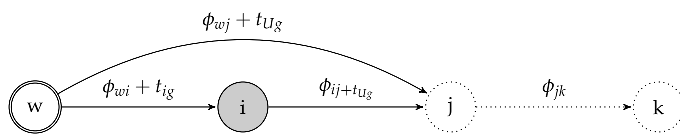


Figure A.4: *Country i faces a trade-off between control and customs union-effect*

$$\max_{\gamma_i^u \in \{0,1\}} \left((1 - \gamma_i^u)\, R_{ig} + \gamma_i^u \frac{D_i}{D_i + D_j} R_u \right) \tag{21}$$

We set up the revenue function from independent i and the union u, and undertake some comparative statics as in Proposition 4. The intuition is the following. The country gives up its geographic position, and control over transit trade. It receives a share of the union's revenues that is independent of the income when independent, as transit trade is neglected. The control the country gives up when joining is higher when physical transport costs (hence the detour costs) are high, so that transport costs represent a considerable share of the price to the consumer.

□

Decision to join a Customs Union

We established that the decision as to whether to join a customs union depends on the sizes and geographic location of states.

Theorem. *Revenue-maximizing states trade off geography-induced positive effects from joining a customs union with their loss of transit revenue due to losing an advantageous geographic location.*

Proof. Consider figure A.4. There exists a customs union $U = \{j, k\}$. Country i can decide whether to form a customs union $U' = \{i, j, k\}$. From Equation 18 it follows that i faces a binary decision between the revenue from staying independent, R_i, and its exogenous determined share $\pi_i^{U'}$ of the customs union's revenue $\pi_i^{U'} R_{U'}$.

We established that there is a positive effect from joining the customs union (Proposition 4). In contrast, if a country is in total control of access to world markets, there is a loss from joining the customs union (Proposition 5). As outlined in the two country case, there is also Bertrand competition over routes that limits the tariff rates.

With increasing world market price, the network effect grows faster than the control effect.

To proof this, set up first derivative of network effect and the control effect w.r.t p_w. The first derivative of the difference between customs union effect and control effect can never be negative under the assumption that all variables are positive and there is demand in all countries. Therefore with increasing world market price, the union becomes more attractive. □

Generalizing the Results

The inspiration for our theory is Irwin (1998), and we extended his revenue-maximizing tariff framework by adding relative geography. Irwin starts with a linear demand function for simplicity, but we can apply the findings of this model for a wider set of demand functions. This will help us to simulate the model with a more appropriate demand function, namely one with a single elasticity.

Generalizing equation 1, we can model the demand for an imported good $M_i \geq 0$ as the result of a function Λ,

$$M_i = \Lambda(p_i, \xi) \tag{22}$$

where p_i is the price on good in i as defined before. The set ξ contains parameters specific to the functional form. The fact that the price of good in i is itself a function of the tariff t_i (equation 3) can be used to rewrite the above more explicitly as

$$M_i = \Lambda(p_i, t_i, \xi) \tag{23}$$

Equations 22 and 23 encompass linear demand functions such as equation 1, where $\xi = \{D_i, a\}$. Our generalized revenue function in analogy to equation 4 can be stated as

$$R_i^I = \max_{t_i^I} \left(t_i^I \Lambda \left(p_i, t_i^I, \xi \right) \right). \tag{24}$$

In equation 5, we retrieved this optimal tariff for an isolated state ("island tariff") by taking the partial derivative of this revenue function with respect to t_i:

$$\frac{\partial R_i^I}{\partial t} = 0 \tag{25}$$

$$\Leftrightarrow \Lambda\left(p_i, t_i^I, \xi\right) + t_i^I \frac{\partial \Lambda\left(p_i, t_i^I, \xi\right)}{\partial t_i^I} = 0 \tag{26}$$

As such, we have to condition the properties of function Λ to ensure the existence of such a point, such as

$$\forall \Lambda\left(p_i, t_i^I, \xi\right) \exists t_i^I : \Lambda\left(p_i, t_i^I, \xi\right) + t_i^I \frac{\partial \Lambda\left(p_i, t_i^I, \xi\right)}{\partial t_i^I} = 0 \tag{27}$$

It is straightforward to see that all steps that follow equation 5 can be, without loss of generality, undertaken with any demand function Λ defined as in equation 23 that meets this condition.

Conclusion on the model

To summarize, our theoretical framework establishes a link between geographic location and trade policy, via transit trade. We first considered the behavior of a single revenue-maximizing state, as in Irwin (1998), then added a second state to model revenues from transit trade and relative geography, third states to capture competition over transit trade, and finally examined the conditions under which states have an incentive to form a customs union. The model can rationalize the reduced form evidence on the strong correlation between transit trade via Prussia and the decision of states to join the Zollverein, as well as the stark differences between German states.

Further, the model implies that there may be competition between states or between customs unions over trade and tariff revenue. Specifically, the decision of one state to join a customs union can change trade costs and least costs paths, and hence the incentives of other states to do so.

However, the framework does not lend itself to a direct empirical test, due to strategic complementarities (and in fact, a lack of data). Instead, we will simulate the model calibrated to historical data using PostGIS. For several points in time, we will take state borders and existing trade agreements as given and simulate the resulting optimal tariffs and tariff revenues for several key states. We show that the model can replicate the series of customs union formation and dissolution that preceded the formation of the Zollverein between 1818 and 1833/34 quite well. Finally, we use this calibrated model to simulate the effect of a set of counterfactual state borders, which have historical plausibility.

Parametrization of our Simulations

In this section, we explain how we used simulations with a parameterized and extended version of our model to calculate tariff revenues.

Discussion of the Demand Function

For our simulations, we move away from the world of linear demand from Irwin (1998) and rely on a combination of a constant elasticity of substitution (CES) and a choke quantity. CES allows us to calculate elasticities for our goods from historical data. The choke quantity ensures that our optimization problem is well-behaved.

More formally, we calculate the demand for any good g in any location i as a function of the goods price at i, p_{gi}, the good's global elasticity $\eta_g < 0$, a product-specific global factor β_g, and a choke quantity c so that[5]

$$D_{gi} = \begin{cases} \beta_g p_g^{\eta_g} & \text{if } \beta_g p_g^{\eta_g} \geq c \\ 0 & \text{otherwise} \end{cases}. \tag{28}$$

Proposition 6. *The theoretical predictions of our model apply, following the discussion before, for all demand functions that can be rewritten as in equation 22 and fulfill condition 27. This is true for equation 28.*

Proof. We can rewrite D_{gi} as $\Lambda(p_i, t_i, \xi)$ with $\xi = \{\beta_g, \eta_g, c\}$. We first need to show that there exists a price at which the partial derivative of the resulting revenue function[6] with regards to the tariff is zero. To do so, consider the top case that evaluates to $\beta_g p_g^{\eta_g}$ if $\beta_g p_g^{\eta_g} \geq c$. To find the optimal tariff, we focus on the effect of an increase in tariffs, and take all other elements of the price from equation 3 as given. As such, we can rewrite

[5] See discussion under choke price on page xvi.

[6] See equation 23.

$$\beta_g p_g^{\eta_g} = \beta_g p_g \left(t_i^I\right)^{\eta_g} \tag{29}$$

for any tariff rate. With a move from a tariff rate t_i^I to a higher rate t_i^{I*}, we gain

$$\eta_g < 0 \text{ and } t_i^{I*} > t_i^I \Rightarrow \beta_g p_g \left(t_i^I\right)^{\eta_g} < \beta_g p_g \left(t_i^{I*}\right)^{\eta_g} \tag{30}$$

This means that, with the increasing tariff rate, $\beta_g p_g^{\eta_g}$ approaches zero in an asymptotic way because p_g is positively correlated with t_i (equation 3) and $\eta_g < 0$. Assuming that all other parameters are set so that $\beta_g p_g^{\eta_g} \geq c$ initially, an increase of the tariff rate will eventually decrease the $\beta_g p_g^{\eta_g}$ below c, which means that D_{gi} evaluates the *otherwise* case and returns zero. Formally, we learn that there must be a marginal t_i^{I*} which is just large enough to choke the demand,

$$\forall t_i^I \exists t_i^{I*} > t_i^I : \text{ if } \eta_g < 0 \text{ and } \beta_g p_g \left(t_i^I\right)^{\eta_g} \geq c \text{ and } \beta_g p_g \left(t_i^{I*}\right)^{\eta_g} < c \Rightarrow D_{gi}\left(t_i^{I*}\right) = 0. \tag{31}$$

This is precisely when changes in the tariff lead us to the *otherwise* case. This is first the case when we set t_i^I so that $\beta_g p_g^{\eta_g}$ is c minus a very small number, and retrieve

$$\lim_{t_i^I : \beta_g p_g^{\eta_g} \to c} \frac{\partial \Lambda\left(p_i, t_i^I, \xi\right)}{\partial t_i} = -\infty. \tag{32}$$

At this point, any marginal increase in the tariff (by the very small number) reduces the overall demand to zero. From equation 4 it follows that also the revenue is zero in this case. The intuition of this finding is that states can use the demand function in equation 28 to maximize their tariff revenue, because it informs them under which conditions a marginal increase in the tariff rate would reduce their revenues (therefore they might not consider it, if this would choke transit trade destined a state that would otherwise provide them with significant revenues). Given that states maximize their revenue *from trade to all destinations whose trade transits their territory*, this implies that their optimal tariff is marginally smaller than the choke price of a destination their revenue significantly depends on. This however does not imply that this is also the choke price of all other destinations–because the other elements of the price—namely the different physical transport costs—matter.

More formally, equation 32 implies that the demand function in equation 28 meets the requirement imposed by equation 27. □

Calibration

We retrieved all the parameters on the right hand of equation 28 from historical sources as follows. We converted all monetary values to Mark using its silver equivalent of 5.55g for convenience.

Calculating the elasticity η_g. For each of the goods, we have the import volumes to Prussia from Dieterici (1846) and London prices from Clark (2010), from which we deduce the import duties from official UK parliamentary records to obtain free on board prices. We ran simple log-log regressions of the first, explaining the latter using data from 1825 to 1830. The coefficients can be straightforwardly interpreted as the elasticity of demand. This yields

$$\begin{aligned} \eta_{Coffee} &= -0.55 \\ \eta_{Sugar} &= -3.70 \\ \eta_{Spirits} &= -2.10 \end{aligned} \tag{33}$$

Weighing the income elasticities of these goods in our basket by their shares yields an elasticity of -2.344 for the entire basket.

Calculating the price p_g. Since we cannot rely on the endogenous prices within Prussia, we again assume London prices from Clark (2010) deduced by the UK duties as exogenous. To gain an average FOB price in Prussia, we calculate the price of the cheapest routes from London to all the capitals of Prussian provinces, and weigh these according to the population of these provinces, as displayed in Table A.1. Finally, we deduce the Prussian tariffs. Again weighing these prices by their shares in our basket, we gain an average basket price in Prussia of 10.22 Mark.

Calculating the demand factor β. After these steps, all parameters in 28 are known, except for β and D. Since we would like to run our simulation with per-capita demand and then use population data to impute regional demands, it is now important to use per-capita demands from Dieterici (1846). We can then re-arrange and solve for β, which yields 2.89.

Choke quantity. The main argument of our simulation is that our agents, the revenue-maximizing states, set the tariffs optimally, observing the demand. To make sure that this optimization always has a solution, it is important to introduce a choke mechanism for cases in which the optimal tariff would otherwise be infinitely high. With an eye on historical background, we decided to introduce a choke quantity. This is a quantity of baskets per capita below which it is logistically nonsensical to import coffee, port, or sugar to a region, and reflects the observation that a lot of regions hardly had any of these goods in general consumption, especially before the Zollverein. In order to obtain the choke price, we used the geography before 1828 to run simulation aimed at predicting the actual recorded customs revenue of Prussia for this period. Onishi (1973, p. 115) reports an average of 8.8 million Reichstaler. We were able to approximate this value using a choke quantity of 2.75kg of our basket per capita.

Further Tables and Maps

Table A.1: *The population of the Prussian provinces along with the physical transport costs (no tariffs) from London coming from our GIS estimates*

Province	Population	Cost of shortest route in M
Münster	1,139,595	16.02983
Danzig	698,103	12.33355
Potsdam	1,430,129	18.62075
Posen	958,806	26.81192
Koblenz	2,031,526	17.65906
Magdeburg	1,313,090	17.08383
Königsberg	1,097,407	13.4815
Breslau	2,194,739	34.41792
Stettin	800,738	9.676754
	Weighted average	20.19903

Table A.2: *Estimates for per-kilometer freight rates from Sombart (1902)*

Type	**Cost [Pf/tkm]**
Country road	120
Paved roads ('Chausee')	30
River, downstream	0.7
River, upstream	1.8
Sea freight	0.95

Table A.3: *List of the 50 states with the 73 locations used for the simulations. Sea harbors marked with a ✓ indicate larger harbors that have a sea connection to London. Apart from London, we included 8 territories which would never join the Zollverein (printed in italics)*

State name	State or Region Capital	Sea harbor	State name	State or Region Capital	Sea harbor
Anhalt-Bernburg	Bernburg		*Austria*	*Brünn*	
Anhalt-Dessau	Dessau			*Graz*	
Anhalt-Köthen	Köthen			*Innsbruck*	
Baden	Karlsruhe			*Laibach*	
Bavaria	Ansbach			*Linz*	
	Augsburg			*Prague*	
	Bayreuth			*Triest*	✓
	Munich			*Vienna*	
	Passau			*Zator*	
	Regensburg		*Poland*	*Warsaw*	
	Speyer		Prussia	Breslau	
	Würzburg			Danzig	✓
Braunschweig	Braunschweig			Koblenz	
Bremen	Bremen	✓		Königsberg	✓
Frankfurt	Frankfurt			Magdeburg	
Great Britain	*London*	✓		Münster	
Hamburg	Hamburg	✓		Posen	
Hanover	Hanover			Potsdam	
Hesse-Darmstadt	Darmstadt			Stettin	✓
Hesse-Homburg	Homburg v. d. H.		Reuß-Greiz	Greiz	
Hesse-Cassel	Cassel		Reuß-Ebersdorf	Ebersdorf	
Hohenzollern-Hechingen	Hechingen		Reuß-Gera	Gera	
Hohenzollern-Sigmaringen	Sigmaringen		Reuß-Lobenstein	Lobenstein	
Holstein	Glückstadt	✓	Reuß-Schleiz	Schleiz	
Krakov	*Krakov*		Sachsen	Dresden	
Lauenburg	Ratzeburg		Sachsen-Coburg-Saalfeld	Coburg	
Liechtenstein	Vaduz		Sachsen-Gotha-Altenburg	Gotha	
Lippe-Detmold	Detmold		Sachsen-Hildburghausen	Hildburghausen	
Lübeck	Lübeck	✓	Sachsen-Meiningen	Meiningen	
Luxemburg	Luxemburg		Sachsen-Weimar-Eisenach	Weimar	
Mecklenburg-Schwerin	Schwerin	✓	Schaumburg-Lippe	Bückeburg	
Mecklenburg-Strelitz	Neustrelitz		Schleswig	Schleswig	✓
Nassau	Wiesbaden		Schwarzburg-Rudolstadt	Rudolstadt	
Neuenburg (Neuchâtel)	*Neuenburg (Neuchâtel)*		Schwarzburg-Sondershausen	Sondershausen	
Oldenbourg	Oldenbourg		*Switzerland*	*Bern*	
			Netherlands	*Amsterdam*	✓
			Waldeck	Arolsen	
			Württemberg	Stuttgart	

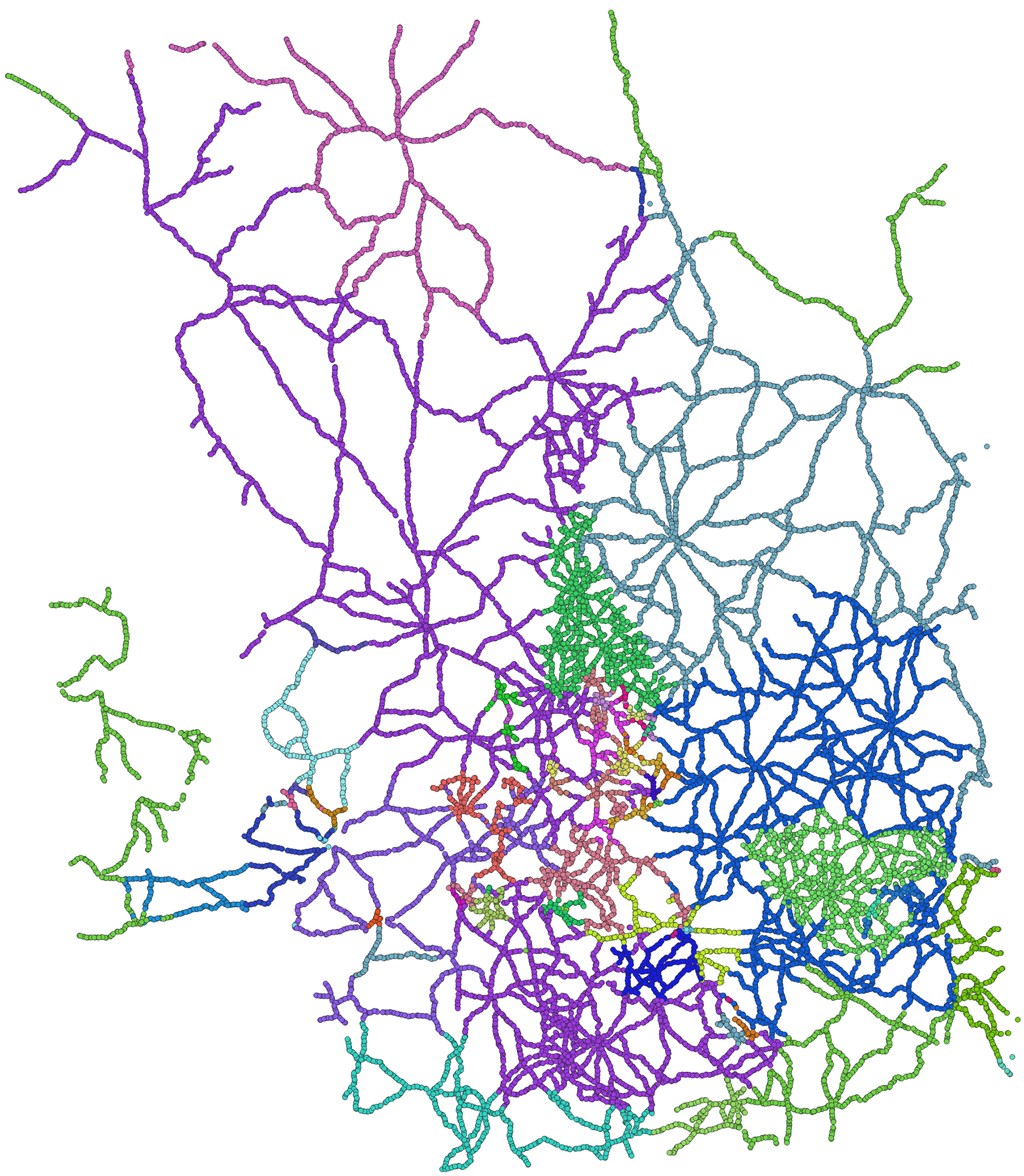


Figure A.5: *Nodes of the transport network for the German lands. These are street points, harbors, provincial capitals, and river turns. The colors indicate the country in which they are positioned.*

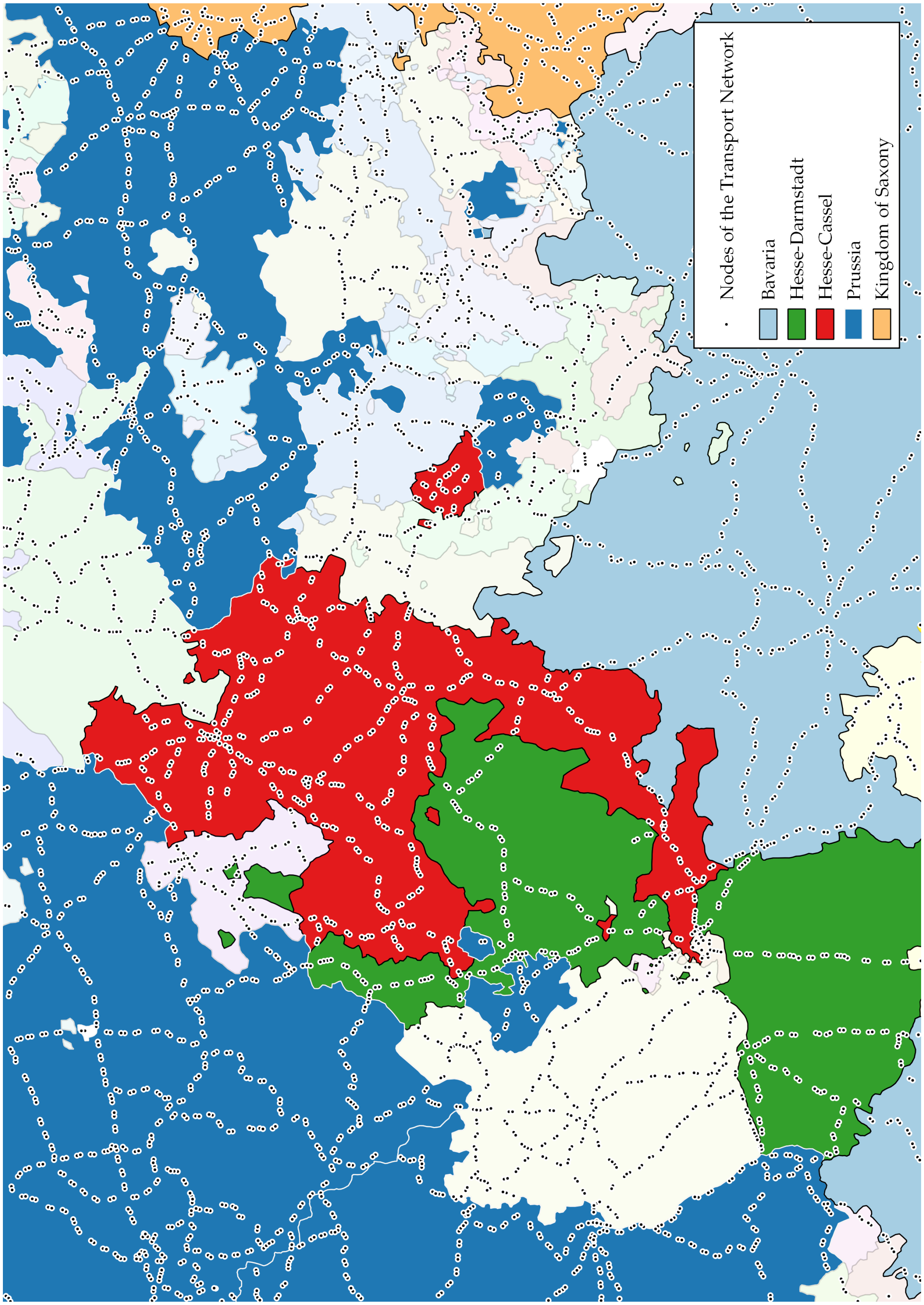
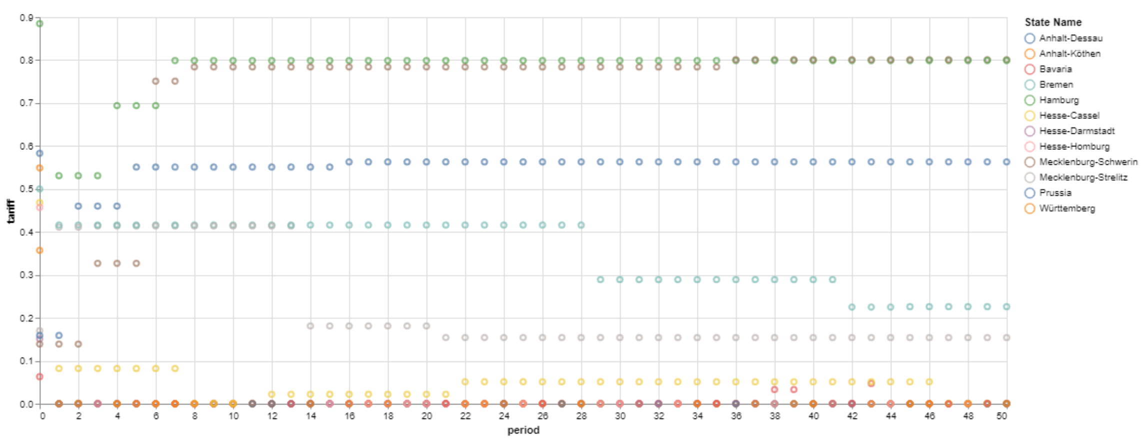


Figure A.6: *Transport network zoomed to the central states, Hesse-Cassel and Hesse-Darmstadt, as well as their surrounding.*

Table A.4: *Summary statistics of the regression exercise*

	(1)	(2)	(3)	(4)	(5)
VARIABLES	N	mean	sd	min	max
Sea harbor	34	0.118	0.327	0	1
Transits Prussia	34	0.412	0.500	0	1
Population	34	367,762	730,144	10,000	3.781 Mio.
Year of joining	34	1,839	14.42	1,824	1,884
Distance to oceans	34	266.0	126.5	6.767	443.4
Absolute monarchy	34	0.529	0.507	0	1
Population (std.)	34	0	1.000	-0.490	4.674
Distance to oceans (std.)	34	0	1.000	-2.050	1.403

Figure A.7: *Simulated tariffs, where states set their optimal tariff rate independently and in alphabetical order, assuming the factual geography of the German lands in 1820*



Note: The simulation is calibrated with the described demand function and includes 49 states from Table A.6 of the Appendix. This figure shows a representative subset of states and how they increase their tariff rates to maximize revenue in several steps, until the simulation is steady. When we insert these tariffs and the physical costs coming from our calculation of the corresponding least-cost paths into the demand function of all states, we can calculate import volumes, and also all states' tariff revenues.

Table A.5: *Parameters of the simulation*

Parameter	Letter	Value	Description	Source
World market price	p_w	9.359 M	Average London prices 1822–1831[a]	Clark 2010
Market size	β		Population data 1820	Kunz and Zipf 2008
Elasticity of demand	η	-2.344	Own calculations	
Choke quantity		2.75 kg per capita	Own simulations	
Physical transport costs	ϕ		GIS map of central Europe 1820[b], including harbors, rivers, roads, and country shapes. Per-kilometer rates[c] are constant per weight, discriminated by transport mode. These are (in the order of increasing per-kilometer price) river transport with the stream, sea freight, river transport against the stream, land transport on paved roads, and land transport elsewhere. Switching transport modes is possible anywhere in which transport lines cross. Transportation costs are independent of the quality and/or category of the good. The transportation costs of a liter is assumed to correspond to that of one kilogram. Gross weight equals tare weight.	GIS maps from Kunz and Zipf 2008 and own maps. Per-kilometer rates and transshipment costs from Sombart 1902

[a] Values were standardized using reported prices in grams of silver.
[b] Rivers were turned into floating direction. Roads were added from own maps. Sea harbors were included.
[c] Values were converted using currency's silver content.

Table A.6: *Summary statistics of tariff rates in a hundred simulations with 1820 factual geography. Indexed to the mean of Prussia (=100)*

State Name	Mean	SD	Min	Max
Prussia	*100*	*19*	*15*	*143*
Anhalt-Bernburg	99	40	25	170
Anhalt-Dessau	61	35	0	153
Anhalt-Köthen	72	37	0	145
Baden	62	26	2	104
Bavaria	59	28	3	115
Brunswick	268	59	51	370
Bremen	98	33	32	163
Frankfurt	148	41	37	255
Hamburg	451	63	8	473
Hanover	89	30	27	188
Hesse-Darmstadt	69	25	4	142
Hesse-Homburg	205	43	35	281
Hesse-Cassel	83	39	2	189
Hohenzollern-Hechingen	1	1	0	2
Hohenzollern-Sigmaringen	1	0	0	2
Holstein	451	63	7	473
Krakov	231	89	87	375
Lauenburg	152	28	20	198
Liechtenstein	0	0	0	0
Lippe-Detmold	83	65	0	190
Lübeck	154	27	18	202
Luxemburg	368	61	39	424
Mecklenburg-Schwerin	195	58	54	281
Mecklenburg-Strelitz	148	29	23	204
Nassau	68	21	19	125
Neuenburg(Neuchâtel)	0	0	0	0
Oldenburg	112	73	33	345
Austria	181	32	23	244
Poland	348	50	17	388
Reuß ältere Linie	0	0	0	0
Reuß-Ebersdorf	0	0	0	0
Reuß-Gera	0	0	0	1
Reuß-Lobenstein	0	0	0	0
Reuß-Schleiz	0	0	0	0
Saxony	144	27	21	189
Saxony-Coburg-Saalfeld	0	1	0	4
Saxony-Gotha-Altenburg	27	40	0	157
Saxony-Hildburghausen	0	0	0	1
Saxony-Meiningen	3	12	0	73
Saxony-Weimar-Eisenach	123	29	25	186
Schaumburg-Lippe	45	34	0	110
Schleswig	451	63	7	473
Schwarzburg-Rudolstadt	35	55	0	192
Schwarzburg-Sondershausen	17	34	0	133
Switzerland	0	0	0	0
Netherlands	79	24	22	153
Waldeck	191	46	40	274
Württemberg	14	20	0	84

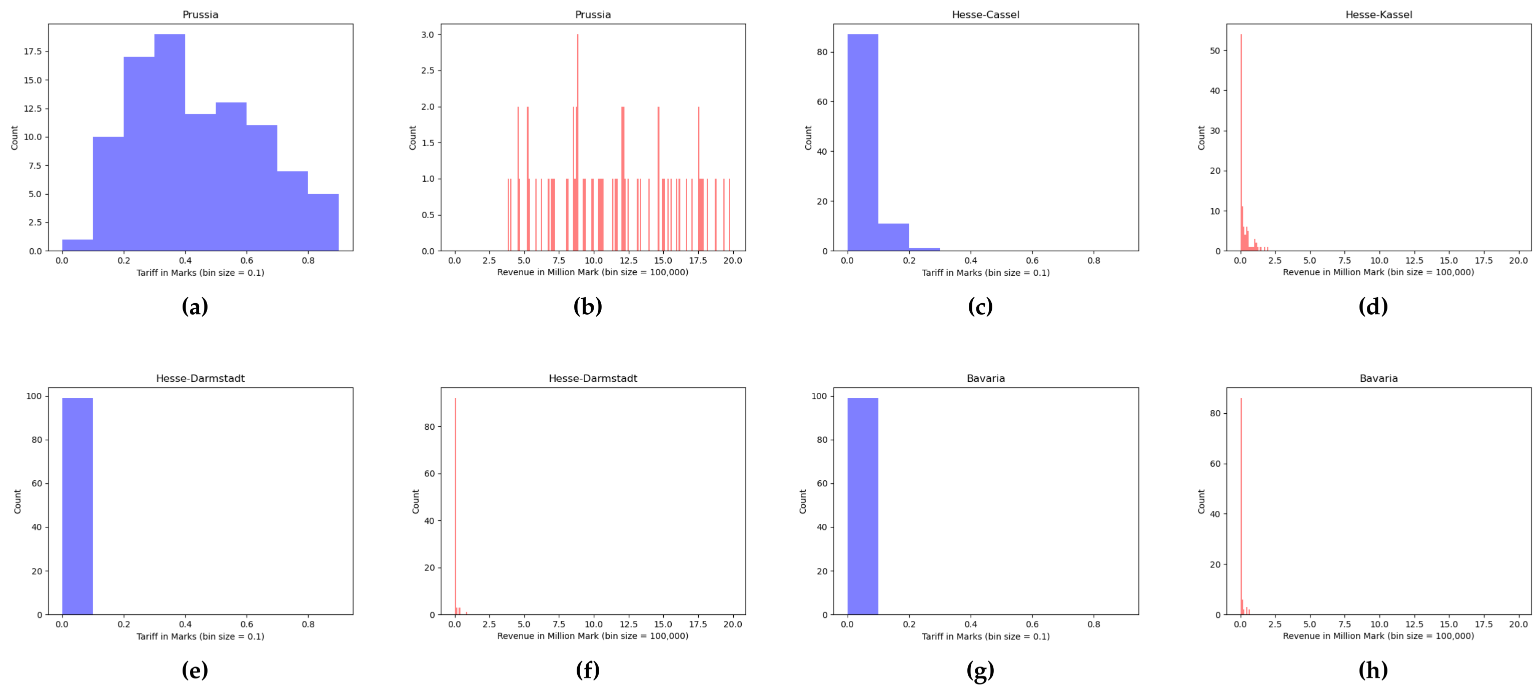


Figure A.8: *Histogram of a hundred simulations in which states decide for 50 periods of random order*

Note: These simulations are based on the factual geography in 1820 and include 49 states that set their tariff rate to maximize their tariff revenue (excluding the UK). These histograms show the distribution of the optimal tariff rates in a hundred different simulations for central states. In figures **(a)** and **(b)**, we see that Prussia can expect to raise more than 4 Million Mark in tariff revenue from the three goods we simulate. The recorded average from Onishi (1973) of 16,3 Mio. Mark is also safely within this distribution. The only other country from this selection is Hesse-Kassel, in figures **(c)** and **(d)**. The other Hessian state, Darmstadt (figures **(e)** and **(f)**), can hardly expect sizable revenue from tariffs, Bavaria, as shown in figures **(g)** and **(h)**, despite being more populous than the Hessian state can expect no revenue in most simulations. These graphs show that the situation for landlocked countries in the absence of tariff cooperation (for example by forming a customs union with Prussia) were bleak.

Table A.7: *Replication of our main results in Table 3 of our article, but with a demand elasticity of −.3. Simulated tariff revenues per capita of selected states, following the historic sequence of decisions to join the German Zollverein, indexed to Prussia 1827 (= 100).*

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Type of Simulation	Simulation the historical customs borders	Simulation the historical customs borders	Simulation of plausible counterfactual customs borders	Simulation the historical customs borders	Simulation of plausible counterfactual customs borders	Simulation the historical customs borders	Simulation the historical customs borders	Simulation the historical customs borders
Description	Late 1827: Prussian CU including enclaves	January 1828: Prussian CU with Southern German CU	February 1828: Hesse-Darmstadt joins Southern CU	February 1828: Hesse-Darmstadt joins Prussian CU	May 1829: Southern CU joins Prussian CU after preliminary treaty	March 1831: formation of Belgium and Mainz Convention opens the Rhine, assumption: Southern CU stay out	August 1831: Hesse-Cassel joins Prussian CU, assumption: Southern CU stay out	March 1833: Zollverein (merger between Prussian and Southern German Customs Union)
Prussian Customs Union	100	109.49	96.22	91.9	77.88	108.58	106.93	82.25
	(80.33,115.14)	(95.63,139.55)	(80.44,126.07)	(73.93,123.45)	(66.26,87.26)	(92.48,125.11)	(93.34,121.75)	(58.32,94.99)
	(55.22,> 200)	(71.91,> 200)	(56.08, > 200)	(52.93,> 200)	(49.36,> 200)	(59.86,> 200)	(66.47,> 200)	(36.83,> 200)
Bavaria	0.21	0.27	0.27	0.16	77.88	0.11	0.16	82.25
	(0.16,1.28)	(0.16,1.6)	(0.11,2.24)	(0.11,0.69)	(66.26,87.26)	(0,0.69)	(0,1.44)	(58.32,94.99)
	(0.05,> 200)	(0.05,> 200)	(0.05,> 200)	(0,> 200)	(49.36,> 200)	(0,> 200)	(0,> 200)	(36.83,> 200)
Württemberg	0	0.27	0.27	0.16	77.88	0.11	0.16	82.25
	(0,0.11)	(0.16,1.6)	(0.11,2.24)	(0.11,0.69)	(66.26,87.26)	(0,0.69)	(0,1.44)	(58.32,94.99)
	(0,> 200)	(0.05,> 200)	(0.05,> 200)	(0,> 200)	(49.36,> 200)	(0,> 200)	(0,> 200)	(36.83,> 200)
Hesse-Darmstadt	0	2.61	0.27	91.9	77.88	108.58	106.93	82.25
	(0,1.65)	(1.55,22.12)	(0.11,2.24)	(73.93,123.45)	(66.26,87.26)	(92.48,125.11)	(93.34,121.75)	(58.32,94.99)
	(0,> 200)	(0,> 200)	(0.05,> 200)	(52.93,> 200)	(49.36,> 200)	(59.86,> 200)	(66.47,> 200)	(36.83,> 200)
Hesse-Cassel	36.62	27.56	21.32	22.39	3.52	2.45	106.93	82.25
	(15.09,73.56)	(6.4,42.38)	(10.93,48.19)	(8.64,58.1)	(0.48,7.3)	(0.85,5.22)	(93.34,121.75)	(58.32,94.99)
	(1.92,> 200)	(1.49,> 200)	(1.76,> 200)	(0.96,> 200)	(0.37,> 200)	(0.32,> 200)	(66.47,> 200)	(36.83,> 200)

Note: These simulations are based on the GIS maps of the European geography and calibration parameters as in table A.5. The first number reports the crude average of the simulated tariff revenues. The numbers in the first brackets indicate the interval between the 40^{th} and the 60^{th} percentiles of its distribution; the second bracket reports the interval between the 25^{th} and the 75^{th} percentile respectively. The changes due to the Belgian Revolution are included by replacing the geographic borders of the Netherlands 1820 with borders of the Netherlands and Belgium as of 1831, each provided with respective population data of 1831, and allowing them to set tariffs independently.

Table A.8: *Replication of our counterfactual results in Table 4 of our article, but with a demand elasticity of −.3. Simulated tariff revenues per capita of selected states, following the historic sequence of decisions to join the German Zollverein, indexed to Prussia 1827 (= 100).*

	(1)	(2)	(3)	(4)
Type of Simulation	Simulation of plausible counterfactual customs borders			
	Independent Counterfactual Prussia, Rhineland-Westphalia, Hesse, Southern CU	Merger between Prussia, Hessian states and Southern CU, excl. Rhineland	Formation of a West-German CU, excluding Prussia	Formation of a Customs Union between Counterfactual Prussia, Rhineland-Westphalia, Hesse, Southern CU
Prussian Customs Union, incl. Saxony	100	27.67	89.24	48.03
	(75.36,120.11)	(23.76,38.51)	(72.04,102.2)	(41.21,57.54)
	(52.39,> 200)	(16.54,> 200)	(54.3,> 200)	(31.33,> 200)
Bavaria	0.91	27.67	22.39	48.03
	(0.17,2.45)	(23.76,38.51)	(16.74,28.25)	(41.21,57.54)
	(0.12,> 200)	(16.54,> 200)	(14.58,>200)	(31.33,>200)
Württemberg	0.91	27.67	22.39	48.03
	(0.17,2.45)	(23.76,38.51)	(16.74,28.25)	(41.21,57.54)
	(0.12,>200)	(16.54,>200)	(14.58,>200)	(31.33,>200)
Hesse-Darmstadt	7.52	27.67	22.39	48.03
	(1.29,14.91)	(23.76,38.51)	(16.74,28.25)	(41.21,57.54)
	(1.04,>200)	(16.54,>200)	(14.58,>200)	(31.33,>200)
Hesse-Cassel	1.83	27.67	22.39	48.03
	(1.29,14.91)	(23.76,38.51)	(16.74,28.25)	(41.21,57.54)
	(1.04,>200)	(16.54,>200)	(14.58,>200)	(31.33,>200)
Independent Rhineland-Westphalia	44.04	21.35	22.39	48.03
	(1.29,14.91)	(23.76,38.51)	(16.74,28.25)	(41.21,57.54)
	(1.04,>200)	(16.54,>200)	(14.58,>200)	(31.33,>200)

Note: These simulations are based on the GIS maps of the European geography and calibration parameters as in table A.5. The first number reports the arithmetic mean of the simulated tariff revenues. The numbers in the first brackets indicate the interval between the 40^{th} and the 60^{th} percentiles of its distribution; the second bracket reports the interval between the 25^{th} and the 75^{th} percentile respectively. The changes due to the Belgian Revolution are included by replacing the geographic borders of the Netherlands 1820 by borders of the Netherlands and Belgium as of 1831, each provided with respective population data of 1831, and allowing them to set tariffs independently.

Table A.9: *Results with a modified geography: Uniform per-kilometer costs. This re-calculates in Table 3 of our article, but there is a uniform per-kilometer rate of 10 Pf/tkm (independent of the mode of transport). Simulated tariff revenues per capita of selected states, following the historic sequence of decisions to join the German Zollverein, indexed to Prussia 1827 (= 100).*

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Type of Simulation	Simulation the historical customs borders	Simulation the historical customs borders	Simulation of plausible counterfactual customs borders	Simulation the historical customs borders	Simulation of plausible counterfactual customs borders	Simulation the historical customs borders	Simulation the historical customs borders	Simulation the historical customs borders
Description	Late 1827: Prussian CU including enclaves	January 1828: Prussian CU with Southern German CU	February 1828: Hesse-Darmstadt joins Southern CU	February 1828: Hesse-Darmstadt joins Prussian CU	May 1829: Southern CU joins Prussian CU after preliminary treaty	March 1831: formation of Belgium and Mainz Convention opens the Rhine, assumption: Southern CU stay out	August 1831: Hesse-Cassel joins Prussian CU, assumption: Southern CU stay out	March 1833: Zollverein (merger between Prussian and Southern German Customs Union)
Prussian Customs Union	100	111.65	93.19	125.49	83.96	166.15	160.66	97.36
	(79.04,115.87)	(112.6,150.42)	(94.99,122.7)	(85.19,117.31)	(76.84,98.56)	(101.37,135.84)	(46.01,72.59)	(92.94,132.95)
	(60.36,144.8)	(81.4,173.27)	(58.47,154.14)	(63.4,140.7)	(54.21,115.87)	(71.45,165)	(34.17,95.9)	(67.88,146.32)
Bavaria	14.07	8.79	9.23	18.9	83.96	44.4	41.54	97.36
	(0.08,0.23)	(0.08,0.3)	(0.08,0.23)	(0.08,0.23)	(76.84,98.56)	(0,0)	(46.01,72.59)	(92.94,132.95)
	(0,0.3)	(0,0.61)	(0,0.46)	(0,0.3)	(54.21,115.87)	(0,0.23)	(34.17,95.9)	(67.88,146.32)
Württemberg	1.32	8.79	9.23	18.9	83.96	44.4	41.54	97.36
	(0,0)	(0.08,0.3)	(0.08,0.23)	(0.08,0.23)	(76.84,98.56)	(0,0)	(46.01,72.59)	(92.94,132.95)
	(0,0)	(0,0.61)	(0,0.46)	(0,0.3)	(54.21,115.87)	(0,0.23)	(34.17,95.9)	(67.88,146.32)
Hesse-Darmstadt	163.3	34.29	9.23	125.49	83.96	166.15	160.66	97.36
	(0,0)	(0,2.35)	(0.08,0.23)	(85.19,117.31)	(76.84,98.56)	(101.37,135.84)	(46.01,72.59)	(92.94,132.95)
	(0,0.23)	(0,6.83)	(0,0.46)	(63.4,140.7)	(54.21,115.87)	(71.45,165)	(34.17,95.9)	(67.88,146.32)
Hesse-Cassel	293.85	282.42	562.64	556.04	522.42	480.44	160.66	97.36
	(2.73,19.21)	(3.04,20.8)	(2.43,20.88)	(1.44,17.39)	(0.53,1.44)	(0.46,1.75)	(0.53,0.61)	(92.94,132.95)
	(0.99,48.52)	(1.21,42.98)	(1.37,41.53)	(0.61,32.57)	(0.46,5.47)	(0.46,3.72)	(0.46,3.19)	(67.88,146.32)

Note: These simulations are based on the GIS maps of the European geography and calibration parameters as in table A.5. The first number reports the arithmetic mean of the simulated tariff revenues. The numbers in the first brackets indicate the interval between the 40th and the 60th percentiles of its distribution; the second bracket reports the interval between the 25th and the 75th percentile respectively. The changes due to the Belgian Revolution are included by replacing the geographic borders of the Netherlands 1820 by borders of the Netherlands and Belgium as of 1831, each provided with respective population data of 1831, and allowing them to set tariffs independently.