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Roads, rails, and checkpoints: Assessing the permeability of nation-state borders worldwide

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ABSTRACT

The permeability of nation-state borders determines the flow of people and commodities between countries and therefore greatly influences many aspects of human development from trade and economic inequality to migration and the ethnic composition of societies worldwide. While past research on the topic has focused on border fortification (walls, fences, etc.) or the legal dimension of border controls, we take a different approach by arguing that transport infrastructure (paths, roads, railroads, ferries) together with political checkpoints can be used as valuable indicators for the permeability of borders worldwide. More and better transport infrastructure increases permeability, whereas checkpoints create the political capacity for reducing entries. Using automated computational methods combined with extensive manual checks, we parse data from OpenStreetMap and the World Food Programme to detect cross-border transport infrastructure and checkpoints. Based on this information, we define an index of border permeability for 312 land borders globally. Subsequent analyses show that regardless of the degree of closure enforcement at checkpoints, Europe and Africa have the most, and the Americas the least, permeable borders worldwide. Regression models reveal that border permeability is higher in densely populated areas and that economic development, by far the most relevant explanatory factor, has a curvilinear relationship with border permeability: Borders of very rich and very poor countries are highly permeable, whereas those of moderately prosperous nation-states are significantly harder to cross. Implications of this remarkably clear pattern are discussed.

1. Introduction

In a world of nation-states, borders between countries play a pivotal role in regulating the transnational mobility of people and commodities and affect many aspects of social, political, and economic reality from trade and development to security to inequality (Simmons, 2005, 2019). In extreme cases, borders can be entirely open or completely shut (Korte, 2021), but commonly, they serve as semi-permeable filters, or "sorting machines" (Mau, 2022), allowing some mobility while inhibiting other cross-border movement (Shachar, 2020: 9). After a period where public debate (and many scholars) prioritized globalization, open markets, and free movement, the pendulum has, to some extent, reversed its course and interest in borders has increased dramatically in recent years. "Borders are back!", remarks one prominent voice in the field (Mau, 2022: 1). Recent crises, from migrants freezing to death at the Belarus-Poland border fence (Tondo & Akinwotu, 2021) to Black refugees being discriminated at the Ukraine-Poland border after escaping Russia's war (Chebil, 2022) highlight the immediate pertinence of borders today.

While a lot of the current research on the topic focuses on border fortification (walls, fences, etc.), the legal dimension of borders and border controls, or the social construction of borders, our project takes a different approach. We argue that *cross-border transport infrastructure* (paths, roads, railroads, and ferries)—together with political checkpoints at these border crossings—can be used as valuable indicators of the permeability of borders worldwide: More and better transport infrastructure increases

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the permeability of a given border segment, while checkpoints provide the political capacity for reducing entries. From this perspective, fortification *along* the border line moves to the background while paths that cut *across* it move to the forefront. We believe there are good arguments for this perspective: Even an infinitely high wall would be penetrable through a door, gate, or gap. Our basic argument is thus that counting the number of "doors," "gaps," and "gates" (as well as the number of "guards" at these "gates") may tell us something about the potential for mobility from one side to the other, perhaps even more so than quantifying the height or the material structure of the wall. For example, no structural change was made to the Berlin Wall on 9 November 1989; the "gates" were simply opened. The Kazungula bridge between Zambia and Botswana is another example. The border line—in this case a natural obstacle, the Zambezi River—did not change when the bridge was inaugurated in May 2021, but it became much easier for cars, trains, and pedestrians to cross to the other side. Therefore, it makes sense to expand research beyond fortification of borders to consider variance in cross-border infrastructure.

To put this approach into empirical practice, we use automatized computational methods combined with extensive manual checks, drawing on OpenStreetMap (OSM) and World Food Programme (WFP) data to parse information on cross-border infrastructure and checkpoints at almost all land borders worldwide. We subsequently use this data (combined with information about border length) to construct a *border permeability index* that indicates how porous a border is in terms of available traffic infrastructure. Our subsequent analyses show that regardless of the degree of closure enforcement at checkpoints, Europe and Africa have the most, and the Americas the least, permeable borders worldwide. Regression models reveal that border permeability is higher in densely populated areas and that economic development, by far the most relevant explanatory factor, has a curvilinear relationship with border permeability: Borders of very rich and very poor countries are highly permeable, whereas those of moderately prosperous nation-states are significantly harder to cross. We discuss implications of this remarkably clear pattern but also make the Border Permeability Dataset publicly available and invite the scientific community to exploit it further (available at https://doi.org/10.5281/zenodo.7457746). The potential utility of the dataset ranges from predicting and explaining human mobility and trade to better understanding development, security, peace and conflict, as well as exploring the connectedness of border permeability with state authority, nationalism and nation-building.

The remainder of this article is structured as follows: We first give an overview of the state of research on borders, situating our own approach relative to others. Next, we provide a conceptualization of this transport-infrastructure-based permeability approach that lays the foundation for the empirical analysis. We then describe the data and methods used to create the border permeability index. Afterwards, the descriptive results show how permeable country borders are in global comparison, what regional differences exist in that regard, and how permeability decreases when border crossings are closed via checkpoint enforcement. Thereafter, the explanatory results reveal, based on a series of regression models, which economic, political, mobility-related, and cultural factors explain the variance in border permeability globally. We end with a critical discussion of the limitations of our data and the implications of our findings.

2. Two current paradigms—and a novel approach

This section first introduces two currently prevailing paradigms in the study of borders: the shifting border and the fortified border.[1] Then, our own perspective (the infrastructurally permeable border) is presented, explaining also how the latter differs from the former two.

The *shifting-border paradigm* argues that borders are increasingly detached from the physical location of the line that is conventionally seen as constituting the territorial border. It argues that states have managed, through legal means, to "shift" the border to control incoming mobility *before* or *after* the departure of migrants and travelers (Mau et al., 2008; Johnson et al., 2011; Geddes, 2012). As a consequence, the selection of who is allowed to enter a territory often does not take place at the geographic border but, e.g., via visa regimes before journeys even begin (Recchi et al., 2021) or in detention centers inside the country after arrival (Bosworth & Vannier, 2020). As the shifting-borders paradigm emphasizes, pushing the border out as far as possible is a deliberate state strategy to pre-sort potential arrivals (Shachar, 2020: 5). This perspective of a "moving barrier" (Ibid.: 4) puts increased emphasis on legal regulations of mobility. It also highlights the complexity of borders as comprising political, social, and cultural elements beyond being mere territorial and geophysical barriers (Flügel-Martinsen et al., 2018).

The *fortified-border paradigm*, by contrast, posits that physical borders actually continue to have relevance today and that a territorial, spatial understanding of borders still merits social-scientific inquiry (Eigmüller & Vobruba, 2016). It points to a revival of border fortification—sometimes called Teichopolitics (Rosière & Jones, 2012)—with the call for building "the wall" under President Trump in the U.S. being a salient example. Contrary to prevailing ideas about a globalized, open world, empirical analyses show that the number of fortified borders worldwide has been drastically increasing over the past decades, especially since the beginning of the 21st century (Ibid.; Hassner & Wittenberg, 2015). While less than 5 percent of country dyads had walled borders in the 1980s, this share increased to more than 20 percent in 2019 (Vallet, 2021: 10). Empirical research under this paradigm examines the degree of fortification at land borders worldwide, differentiating, e.g., between 'no-man's-land' borders, landmark borders, checkpoint borders, barrier borders, and fortified borders (Gülzau & Mau, 2021) or between frontline, fences, walls, and closed straits (Ballif & Rosière, 2009; Rosière & Jones, 2012; Vernon & Zimmermann, 2020).[2]

By contrast, our focus is on the *infrastructurally permeable border*. We argue that putting the spotlight on the traffic infrastructure that *crosses* a border instead of on what happens *along* the border line in terms of fortification is reasonable since the mobility of people and commodities takes place on precisely these routes. Streets, highways, paths, ferries, and railways are the grid on which mobility of both humans and freight takes place. Such traffic infrastructure is therefore the material artefact that indicates where people and things can be (and are being) transported across borders. Just as a trapper can read the traces that game leaves in the wild to understand its motion patterns, we can look at the "paths" that humans (and their goods) use to cross borders in order

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[1] We do not discuss other existing approaches to the study of borders that are less pertinent to our endeavor. For example, we do not engage with the perspective of the "symbolic border," "borderscapes," and practices of "bordering," which focus on issues of belonging, exclusion and inclusion into national communities (Johnson et al., 2011; Mau, 2013: 469; Rauhut & Laine, 2020), nor with more philosophical and theoretical discussions on the nature of borders (cf. Balibar, 2002; Kleinschmidt & Hewel, 2011; Widdis 2021). Due to spatial constraints, we unfortunately also cannot engage with the many valuable case studies on specific borders regularly presented, for instance, in outlets such as the *Journal of Borderland Studies* (e.g., Bewiadzi Akakpo, 2022; Donko et al. 2021).

[2] In addition, the project *Landscapes of Border Control* led by Mary Bosworth has begun to collect qualitative information about border control practices globally (cf. borderlandscapes.law.ox.ac.uk, accessed 10/4/2022).

to understand how permeable national borders are. From this perspective, how fortified the border is becomes secondary. A border does not need to be heavily secured through walls and barbwire to be non-permeable. Natural obstacles—from dense jungle to deserts—can have a similar effect. A prominent example is the Darién Gap between Colombia and Panama where the Pan-American Highway is interrupted due to dense rainforest, making border-crossings notoriously hard (Rosière & Jones, 2012: 233; Shah, 2020). But even a green border in a moderate climate would be hard to cross if there was no adequate traffic infrastructure (e.g., due to a lack of demand in sparsely populated areas). Traffic infrastructure should thus be an excellent indicator of how permeable a border is for the mobility of persons and goods, irrespective of climate conditions.

Yet, this approach will of course only provide us with an *approximate* measure of permeability, i.e., the infrastructural *potential* for crossing from one side to the other. "Permeability" should not be equated with the actual degree to which these borders are penetrated by people and commodities daily. In theory, a superhighway between two countries could remain empty and dysfunctional if it was not built to meet travel demand but, e.g., as a political prestige project. In general, some roads—even of the same width and condition—will see more traffic than others. What we will measure here is thus the theoretical degree of penetrability. The strength of its correlation with actual mobility flows is, in fact, an empirical question. To use another metaphor: We count the number of arteries and veins, not the quantity of blood that pumps through them.

In addition, we need to take into account that these veins and arteries can be blocked, e.g., when a landslide destroys a road, or, more importantly, when political controls reduce the throughput at border checkpoints. Both cases will have to be taken into account: First, non-usable infrastructure cannot contribute to permeability (empirically, the infrastructure attributes 'abandoned,' 'razed,' 'disused,' and 'under construction' in our dataset will designate such cases—more on this below). Second, we need to recognize border checkpoints, which can enforce (through police or military) partial or complete blockages of cross-border traffic infrastructure. How exactly this can be conceptualized and operationalized is described in the following sections.

3. Conceptualizing the infrastructure-based border permeability perspective

The infrastructural approach to border permeability is illustrated in Fig. 1. Consider a border segment of a specific length, say 100 kilometers (Panel A). If there is just one road that crosses this border segment, then the permeability of the border segment will be relatively low (Panel B). People and commodities may still cross elsewhere by foot if it is a flat border, but transport of larger quantities of persons or goods will be difficult and slow. In our conceptualization, we make the assumption that these potential cross-border flows can be neglected. Any type of regular, non-negligible cross-border mobility should result in the creation of at least a narrow footpath or an unpaved track, which would then be covered in our data as relevant border-crossing transport infrastructure. Of course, broader roads of better quality allow for more throughput and thus need to receive more weight (more on this below).

If more roads cross the border segment, the permeability is higher, as illustrated in Panel C. Of course, roads are not the only relevant type of transport infrastructure. Another example are railway tracks. If railway tracks cross the border in addition to roads, the permeability increases further (Panel D). In short, the more transport infrastructure crosses a border, the higher the border permeability, ceteris paribus. Roads and railways are just (the most common) examples to illustrate the diversity of traffic infrastructure. Empirically, we will have to deal with a larger variety of such infrastructure, from highways to bridleways to cycleways (cf. Appendix Table A1).

As discussed in the previous section, the permeability created by transport infrastructure can be reduced through political controls via *border checkpoints*. A checkpoint can be used to selectively reduce the throughput of people and commodities at a certain border-crossing. The degree of this reduction can vary, though. We can imagine a border checkpoint that completely shuts down a border-crossing road, another one that reduces throughput by 50 percent, or one where all passing cars are waived through without any traffic reduction. For now, let's assume that checkpoints are typically used to reduce the permeability of a border-crossing transport infrastructure to *some* extent, whatever its precise value. Even if checkpoints are able to reduce border permeability, the reduction will be low if there are few checkpoints and many cross-border roads and railways (Panel E). However, if almost every border-crossing transport infrastructure features a checkpoint (or even two on either side of the border), then the permeability is reduced significantly (Panel F). In theory, even a border that has significant cross-border transport infrastructure can be fully blocked by an equally large number of checkpoints[3] enforcing the lockdown of said infrastructure.

3.1. Constructing the border permeability index

We can now convert these considerations into a quantitative *Border Permeability Index* (BPI). For two countries *A* and *B* that are connected via a common land border, we can compute the BPI as:

$$BPI = \frac{I - (e \times C)}{L} \times s$$

where L is the total length of the border between A and B (in km), I is the border-crossing transport infrastructure (i.e., the number of all roads, railways, paths, etc. that cross this border), and C is the number of border checkpoints. The factor e describes the degree of enforcement, i.e., the political control exercised at the checkpoints on average, ranging from $e = 0$, indicating that the checkpoints are actually unused and all persons/vehicles are let through without control, to $e = 1$, indicating that the checkpoints are used to shut down the road (or railway, path, etc.) entirely. We do not have empirical information about e for the checkpoints in our dataset, but we can use the parameter e to show how the permeability of borders changes along the continuum from no enforcement to full enforcement. This is a more effective approach compared to assigning a specific value to e (say 0.3) since in reality the degree of enforcement can be changed politically from one moment to the next. Thus, $e \times C$ captures a state's potential capacity to shut down borders. Finally, s is a factor that normalizes the BPI so that it theoretically runs between 0 and 1 by taking the clustering of border-crossing infrastructure into account. In our operationalization, we have clustered observations using a cluster diameter of 500 meters (more on this below). Accordingly, there is a maximum of 2 cross-border transport infrastructures per kilometer. Hence, without s, the BPI could reach a maximum of 2. To normalize the index, the factor s is set to 0.5. As a result, the BPI can theoretically

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[3] We assume here that a single checkpoint is, in theory, able to reduce mobility *in both directions*. Overall, this study takes a non-directed stance on borders. This is because (a) cross-border traffic infrastructure is *per se* non-directional and (b) we lack empirical information on the degree to which checkpoints are *de facto* used in a directed manner. Also note that often, checkpoints are not always placed exactly on the border line as in the simple illustration in Figure 1. Sometimes, they can be found a bit further inland (in the U.S., e.g., in the 100-mile border zone), and sometimes they are not even fixed booths (e.g., buses can be stopped and trains can be boarded by border patrol officials). More information on how this issue was dealt with empirically follows below.

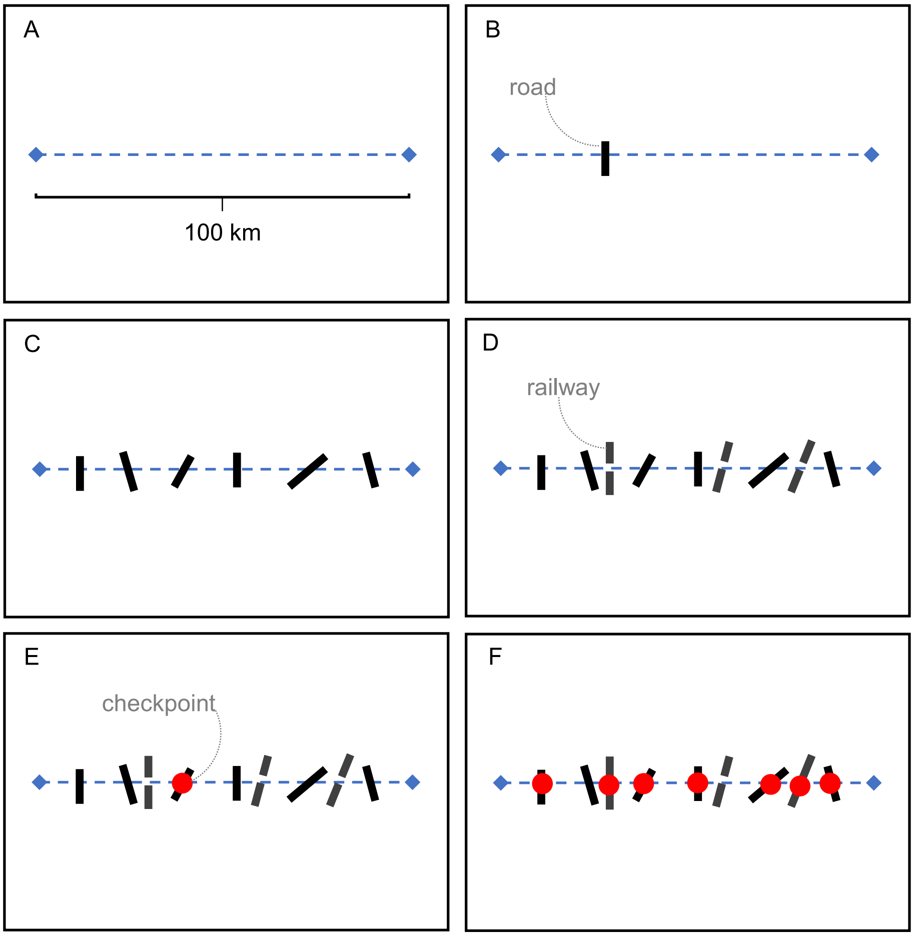

Fig. 1. Conceptualization of border permeability.

run from 0 (no permeability) to 1 (highest possible permeability with at least one infrastructure to cross the border every 500 meters).[4]

3.2. Weighted and unweighted versions of the border permeability index

After these general considerations, a remaining challenge in constructing the BPI is to specify the central component I, the border-crossing transport infrastructure. In the simplified illustration in Fig. 1, we only differentiated between roads and railways as two example types of cross-border infrastructure. However, empirically, our data will contain no less than 38 different specific types, from motorways to footpaths to ferries to narrow-gauge railway tracks (see Tables A1 and A2). This raises the question of how to implement this diversity, doing justice to their relative importance. It seems plausible that major highways or fully-functioning railway tracks permit the transport of larger quantities of people and commodities across borders than a narrow footpath or an unpaved track and should consequently have a bigger impact on the permeability of a border. It is therefore prudent to assign weights to the different types of border-crossing traffic infrastructure:

$$I = w_1 \times i_1 + w_2 \times i_2 + \cdots + w_n \times i_n$$

where w is the weight assigned to a specific type of border-crossing traffic infrastructure (with $n = 38$ in our empirical case) and i is the count of occurrences of a specific type of border-crossing infrastructure (e.g., i_1 = number of motorways, i_7 = number of cycleways, etc.). While this approach has intuitive plausibility, several challenges had to be overcome in practice:

1. To the best of our knowledge, no reliable sources exist on traffic throughput of different infrastructure types that would be fine-grained and globally reliant enough to inform weight-building for the 38 requisite categories.[5] In the absence of such reliable empirical figures, the weights will to some extent be arbitrary. Informed by the descriptions and orders provided by OSM, we developed a simple weighting system which downgrades infrastructure that is narrower or of lower quality (cf. Table A1 in the appendix). For example, some highways are pre-categorized by OSM into “primary,” “secondary,” and “tertiary,” designating a clear order that allows us to downgrade lower-ranking categories. Imperfect as this approach may be, it should lead to a more realistic outcome than a mere additive index that assigns

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[4] This assumes that any checkpoint is connected to one road or railway and that $C \leq I$. Empirically, this is not always the case in our dataset. In a small number of cases, there are more checkpoints than transport infrastructures. This can happen when there are checkpoints on both sides of the border and they are more than 500 meters apart so that the clustering algorithm does not identify them as one clustered checkpoint. As a consequence, when e is set at high levels, a small number of borders reaches a negative permeability value (cf. Table 1).

[5] A popular visualization that indicates passengers throughput for different modes of transportation only differentiates between nine such modes and is partially based on three-decade-old data from the Netherlands (see https://www.transformative-mobility.org/publications/passenger-capacity-of-different-transport-modes, accessed 11/4/2022). Another source also only differentiates between six different street configurations (Babadjanov, 2016). In addition, these sources only measure passenger throughput, while our BPI also aims to capture the penetrability for commodities.

all infrastructure types the same weight. Yet, we will experiment with both this weighted and an unweighted version of the BPI. Doing so will demonstrate that results are very stable independent of concrete weighting decisions. The reason for this stability is that the composition of infrastructure types is very similar across world regions. This implies that the precise size of specific weights has little power to change the overall picture. Furthermore, the published Global Border Permeability Dataset contains information on all 38 individual infrastructure types, allowing researchers to construct alternative weights and compare resulting outcomes to ours.

2. A quarter (25.4 percent, see Table A2) of all usable cross-border infrastructure stems from manual robustness checks, covering infrastructure that was mistakenly missed by the algorithm (false negatives, more on this below), and 0.2 percent is classified by OSM under the infrastructure type "unknown". For these cases, we do not know the exact category (human coders only differentiated between "road or railway" and "ferry") and accordingly, it is difficult to assign a specific weight. As a solution, we assigned these cases the average weight of the categorizable infrastructure that was detected by the algorithm at this specific border. For five borders, this approach did not work, because they had exclusively manually collected cross-border infrastructure. In these exceptional cases, we used the global average weight of all infrastructure.[6]
3. The clustering method (see below) randomly picks one of the infrastructure types when several types co-occur within a cluster. Thus, when such clustering occurs, it is not necessarily the most "important" or most common infrastructure type that gets picked and it is unclear whether the assigned weight is "representative" in this sense. Yet, on average, assignments that are "too low" and assignments that are "too high" should cancel each other out. In the Supplementary Material, we also show that alternative clustering methods that pick the infrastructure with the highest weight or the one that occurs most often are correlated 0.99 with the used random-pick approach and lead to practically identical outcomes.
4. The infrastructure category "track" can either refer to a "special road type" that is used mostly for agricultural or forestry purposes *or* to a bicycle track that provides a route that is separated from traffic (cf. Table A1). Unfortunately, we cannot differentiate between the two in our dataset.[7] This issue was solved by assigning both types of "track" the same weight. Doing so seems reasonable since, in many countries, agricultural and forestry tracks are also used for biking.
5. If infrastructure is weighted, it is not immediately clear how to gauge checkpoints. This is because checkpoints are not assigned to specific roads or rails in our dataset; we merely collect the overall number of infrastructure types and checkpoints for each border. As a consequence, weighting a checkpoint as 1 would reduce the permeability index too much if it was actually located at a type of road weighted, e.g., as 0.7. As a solution, we assigned checkpoints the *average* weight of traffic infrastructure at that specific border (with the exception of the five exceptional cases already mentioned under [2], to which we assign the global average weight). Accordingly, on average, one checkpoint closes one cross-border infrastructure.

Taking these considerations into account, we were able to construct a weighted BPI (and a non-weighted BPI that simply assigns all usable transport infrastructure a weight of 1).

4. Data and methods

Data on borders and transport infrastructure (roads, paths, railways, etc., cf. Table A1 for a complete list with descriptions) was obtained from OSM. OSM is an open-source collaborative mapping platform. Following a similar logic as Wikipedia, its content is created by volunteers. As of 23 May 2021, it had 7.5 million users, of which about 45,000 had made edits to OSM in the preceding month.[8] Already in 2012, OSM was shown to be able to find shorter paths for pedestrians due to the higher completeness of the data compared to commercial providers such as TomTom (Zielstra & Hochmair, 2012). It has also been used repeatedly for scientific research to create, for example, a forest landscape integrity index (Grantham et al., 2020) or to simulate space heating energy demand within cities (Schiefelbein et al., 2019).

The border checkpoint data derives from three sources. The two main sources are OSM and WFP's Global Border Crossing Points dataset.[9] As Panels C and D in Fig. 2 reveal, the two sources are to some extent complementary. The WFP data adds checkpoints in countries where the organization is active, particularly in central Africa, that are missing in the OSM data. First exploratory analyses revealed, however, that the number of checkpoints is still quite low compared to the overall amount of cross-border traffic infrastructure. The low number of checkpoints between Israel and the Palestinian territories, a border that is well-known for being checkpoint-heavy (Rijke, 2021), was particularly puzzling. To fill this gap, we added data on checkpoints from an additional source, B'Tselem (2021), specifically on checkpoints at the Israeli-Palestinian borders.[10] We combine the three datasets by taking, for each land border, the source with the highest count of border checkpoints. Only checkpoints within 10 km of a border are counted, disregarding checkpoints further inland (usually at international airports). Following this strategy, information on a total of 5,931 individual checkpoint booths was collected.

Our starting dataset, collected in September 2019, thus contained geometries representing land borders, transport infrastructure, and checkpoints of all nation-states worldwide. The first task was to identify those transport infrastructures that cross territorial borders. To do so, we applied the geometric primitives made available by the GIS Database PostgreSQL/PostGIS. We intersected the lines that represent the infrastructures (roads, railways, pathways, etc.) with the lines that represent the border between each pair of countries. This technique allowed us to identify the infrastructures that cross national borders. A similar approach was taken to identify checkpoints at land borders globally. The result, shown in Fig. 2, is already quite revealing and points to meaningful global inequalities (consider, e.g., the concentration of railway infrastructure in Europe in Panel B). But to create a usable dataset of border permeability, two additional steps were necessary: clustering and manual checks.

4.1. Clustering

A railway or road infrastructure can be composed of many segments and each of them can cross the border line in the same

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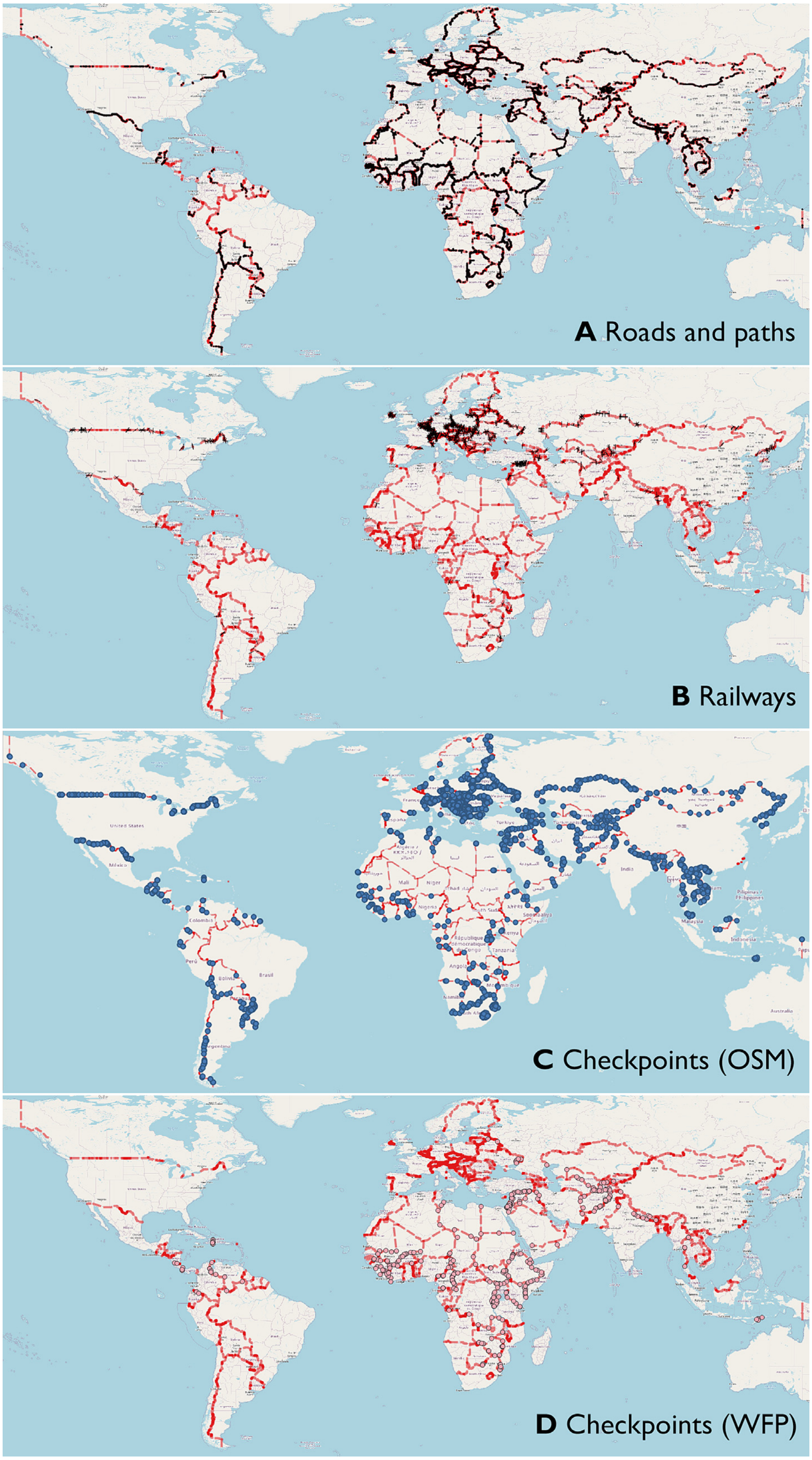
[6] The global average weight is 0.63. The five borders are Costa Rica—Nicaragua, East Timor—Indonesia, Laos—Myanmar, Honduras—El Salvador, and Honduras—Nicaragua.

[7] This is because only what is described as "value" in Table A1 was saved as a variable name, whereas the "key," or *meta*-infrastructure type, was not saved. In all other meaningful infrastructure types, the "value" has a unique name and this problem does not occur (cf. Table A2). Future replications of our method can circumvent this issue by also saving the key. Then, the two infrastructure types can easily be differentiated since agricultural tracks are designated as "highway=track" and cycle tracks as "cycleway=track."

[8] https://www.openstreetmap.org/stats/data_stats.html, accessed 5/24/2021.

[9] https://data.humdata.org/dataset/global-border-crossing-points, accessed 11/4/2022.

[10] OSM and WFP only indicated 9 individual checkpoints for this border, whereas B'Tselem's "List of military checkpoints in the West Bank and Gaza Strip" contains information on 177 checkpoints. This discrepancy suggests that the OSM and WFP checkpoint data might also be incomplete in other countries.



A Roads and paths

B Railways

C Checkpoints (OSM)

D Checkpoints (WFP)

Fig. 2. Cross-border transport infrastructure and border checkpoints at land borders worldwide. Based on OpenStreetMap (OSM, Panels A-C) and World Food Programme (D) data.

stretch. Counting each individually as border-crossing infrastructure could result in a biased outcome. For example, if there is a long border with just one town situated right on a border, the town may have a large number of streets passing through it with only scarce cross-border infrastructure along the rest of the border (for a concrete example case, cf. Supplementary Material). Counting every small residential street and footpath in the town would then misleadingly make it appear as if the overall border had a relatively high permeability. This problem can be resolved by clustering. Clustering means that when more than one cross-border traffic infrastructure was found within a range of 500 meters, only one of them was counted. This was done using the DBSCAN technique. This clustering procedure has the additional advantage of providing the BPI with a theoretical maximum. Given that (a) the clustering radius is set to 250 meters ($\triangleq$ range, or diameter, of 500 meters), (b) no nation-state border has a length of <1 km,[11] and (c) we introduced the normalizing parameter $s = 0.5$, the maximum permeability that can be reached is BPI = 1. Such a high value can only be reached if the entire border has at least one cross-border traffic infrastructure in each 500 meter segment[12]—which makes sense from a theoretical perspective. Checkpoints were clustered, too, using the same clustering radius of 250 meters for the main analyses. This was done because we argue that two individual checkpoint booths at the same road should not count twice. Theoretically, throughput at the road can only be suppressed by 100 percent maximum, not by 200 percent. By clustering checkpoints in the same way that we clustered traffic infrastructure, we ensure that each (clustered) checkpoint corresponds to—and can affect—one (clustered) cross-border infrastructure (for a detailed discussion, additional tests, and alternative model specifications without checkpoint clustering that lead to similar results, cf. Supplementary Material).

4.2. Manual data cleaning

Extensive manual checks were necessary, because sometimes cross-border infrastructure was not correctly identified in the automatized data collection. In large part, this was due to the following issue: For computational efficiency, the geometry that represents the border line had to be slightly simplified. Doing so improved the execution times of geometric queries, making the automatic data collection feasible, but unfortunately also reduced the accuracy of the border line when compared to the high-resolution, ‘‘real” border line as provided by OSM. The discrepancy between the simplified border line and the high-resolution OSM border line is usually no more than a few meters but can, in rare cases, reach a maximum of 100 meters. This discrepancy creates a risk of *false positives*, particularly when a road that *ends* close to the border is mistakenly classified as *crossing* the simplified border. In the manual checks, such false positives were deleted (using an identifier called OSM ID). In addition, *false negatives* occurred. Sometimes, the automatic data collection missed cross-border infrastructure even though it could clearly be identified as such in the manual inspection by human coders (for concrete example cases, cf. Supplementary Material). Furthermore, the manual coders were instructed to create an additional type of cross-border infrastructure, *ferries*, which were not identifiable in the automatized data collection, but which turned out to be important means of transport particularly at borders that are constituted by a river or lake.[13]

This manual data cleaning procedure was time-consuming and extensive. Three human coders manually scrolled along every land border globally in the geographic information system software QGis, usually at a resolution of around 1:14000, checking and registering false positives and false negatives. This procedure took several months to complete. In sum, a total of 6,996 false positives were identified and subsequently deleted, and 7,615 false negatives were identified and accordingly added to the dataset (cf. Supplementary Material for further information). The final, clean Border Permeability Dataset covers 312 land borders globally with 30,045 usable cross-border traffic infrastructures and 2,939 clustered checkpoints.

4.3. Regression model and explanatory variables

To systematically explore which structural factors are associated with the degree of border permeability, we conduct OLS regression models with dyad-adjusted standard errors using country pairs as units of analysis and the log weighted BPI with $e = 0$ as dependent variable (other versions of the BPI are used in robustness checks, cf. Appendix Table A3 and Supplementary Material). While the BPI is not directed (cross-border traffic infrastructure is per se undirected and while checkpoints are *in theory* directed,[14] we lack empirical information about the extent to which they are used selectively depending on direction, making them non-directed *in practice* as well), some explanatory variables are directed. Therefore, the two directions ($A \rightarrow B$ and $B \rightarrow A$) are included in the regression models, which doubles the number of observations compared to a one-directional count of borders (missing values, in turn, reduce the number of observations). As explanatory variables, we include four thematic groups of factors, labeled ‘‘economics,” ‘‘politics,” ‘‘mobility,” and ‘‘culture.”

Economics. First, we include the *gross national income (GNI) per capita* as a measure of economic development.[15] It seems intuitive that richer countries have more resources available to build traffic infrastructure and are also more willing to engage in cross-border activities with their neighbors. However, as we will see in our descriptive results, border permeability is also high among countries at the lower end of the income distribution. A possible explanation is that poor countries have low state capacity and are thus unable to enforce border closures (more on this below). To test for a curvilinear effect of economic development, we also control for the squared term of GNI per capita. Furthermore, we include the absolute GNI per capita differential between the two countries to test whether a

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[11] When a border is very short, the permeability can reach exceptionally high values even when there are ‘‘regular” amounts of border-crossing infrastructure. The most extreme example is the world’s shortest border, between Zambia and Botswana, which is just 0.16 km long. Even with just one ferry crossing it (the Kazungula bridge, mentioned in the introduction, was not yet open at the time of data collection), the BPI would reach a value larger than 6 and would thus constitute an extreme outlier. To avoid such distortions, we decided to drop all borders of <20 km of length from the dataset. Six borders were thus dropped: Zambia-Botswana, Saudi Arabia-Bahrain, Spain-Gibraltar, Monaco-France, Luxembourg-Germany, and Palestinian Territories-Egypt.

[12] A further condition is that the clusters don’t overlap. When many roads cluster together, clusters can actually become larger than 500 meters due to (in this case undesirable) chain effects of the DBSCAN technique. This happened here only in a very small share of cases (1.35 percent for road infrastructure, not at all in the case of railways, which were clustered separately). This issue should have been resolved by the manual cleaning (manual coders assumed a 500 meter maximum cluster range and would add missing infrastructure further away as false negatives). However, to be completely certain that this issue does not affect the presented findings, we additionally constructed an alternative version of the BPI where the few excessively large clusters (>500 meters) were upgraded in that their weight was increased proportionally to their excess size. The findings are not affected, as shown in the Supplementary Material.

[13] Information on border-*crossing* rivers could not be quantified as cross-border infrastructure, even though vessels on waterways (beyond ferries) can, of course, constitute relatively important means of transportation. Our dataset may thus underestimate water-based mobility.

[14] Consider, e.g., that it is usually easier to cross from the U.S. to Mexico than vice versa.

[15] Specifically, we use a logarithmic version of the mean GNI per capita of the two countries on either side of the border, based on World Bank data from 2019.

greater income gap leads to lower permeability. Past research has found that a larger wealth gap explains border fortification (Gülzau and Mau, 2021) and it seems plausible that permeability is similarly affected.

Politics. Border permeability is often about mutual cooperation between states, which control access to their territory, requiring collaboration while building joint transport infrastructure and checkpoints. One could therefore assume that states that cooperate more with each other are connected through more and better infrastructure and fewer checkpoints due to established foundations of trust. To test this assumption, we include a variable that captures the number of *intergovernmental organizations* of which the two countries are joint members.[16] In addition, we test whether more democratic countries have greater border permeability since openness is often seen as a self-defining value of democracies. We do so by including the mean state of democracy of the two countries (measured via The Economist's Democracy Index, EIU, 2018). To further test the impact of domestic politics, we add a measure that captures the share of years a country has been under the leadership of rightist heads of government (as opposed to leftist or centrist ones) between 1945 and 2020, based on the Global Leader Ideology Dataset (Herre, 2022). Here, the assumption is that countries led predominantly by right-wing politicians will focus more on closed borders and put less emphasis on developing cross-border infrastructure. The measure captures the long-term perspective over several decades, which makes sense since transport infrastructure takes time to build.

Mobility. The mobility of people and goods creates a demand for traffic infrastructure and could thus explain border permeability. Human settlement density can, on the one hand, be seen as an indicator for human mobility potential: Where more people live, more people are likely to cross borders, possibly requiring more cross-border infrastructure. On the other hand, human settlement density could also constitute a proxy for geographic accessibility of the terrain, which is challenging to capture empirically. Where terrain is rough (e.g., rain forests, deserts), settlements are usually scarce. Here, we draw on the Global Human Settlement (GHS) spatial raster data (Schiavina et al., 2019) and implement two indicators. *GHS built-up area* captures the density of human-made, built structures based on satellite imagery, whereas *GHS population* captures the population density. In both cases, the variables created by us from the original gridded data capture the mean density in a 10 km band around the border (5 km to either side).

It is difficult to test the relation between border permeability and *actual* human mobility since there is no global data that would exclusively capture mobility via land. As an approximate indicator, we include the mobility variable (estimated trips) from the Global Mobilities Project's (GMP) Global Transnational Mobilities Dataset (imperfect for this purpose since it is partially based on air traffic data: cf. Recchi et al., 2019). Finally, at the intersection of mobility and politics, we include the visa costs countries charge each other for tourist visits, based again on GMP data (Recchi et al., 2021). Countries that charge each other less may have more positive relations and greater travel demand, which could also become visible in higher border permeability.

Culture. A further possibility is that culturally similar countries have closer relations and more cross-border interactions, potentially resulting in higher border permeability (cf. Baud & Van Schendel, 1997: 231-234). To test this idea, we include two indicators of cultural similarity based on the seminal CEPII dataset (Melitz & Toubal, 2014), *common spoken language* and *religious proximity*.

Controls. Finally, the *border length* constitutes an important control variable. While it will be relatively easy for a very small state such as Luxembourg to fill its entire borders with a dense network of traffic infrastructure, it's a lot harder (and probably also unnecessary) for a state like Russia to do so, e.g., along the 12,700 km border with Kazakhstan.

5. Results

The results are presented in two steps: First, we descriptively map the permeability of borders worldwide based on our newly minted, original dataset. Second, we explore the structural determinants of border permeability analytically through a series of regression models.

5.1. Mapping the permeability of borders worldwide

To map border permeability globally, we follow a "zoom-in" approach: we begin with the coarse-grained picture of world regions, then move to the nation-state level, and finally look at individual borders. Starting with a *cross-regional comparative analysis*[17] allows us to get a sense of differences between the weighted and non-weighted versions of the BPI and the impact of the hypothetical enforcement at checkpoints. The top half of Fig. 3 shows the average permeability of borders across six world regions, depending on the degree of enforcement at checkpoints (horizontal axis) and whether the weighted or non-weighted version of the BPI is used (Panel A and B, respectively). Three things are noticeable: *First*, regardless of the index version used, Europe has the highest border permeability, followed by Africa and—at much lower values—the Middle East and Asia, with the Americas ranking lowest. *Second*, the picture looks almost identical in the two panels, suggesting that the weighting actually has little impact on the conclusions that are drawn. While the index does decrease as some infrastructure is weighted down (compare the two vertical axes), the relative position of almost all regions is basically unchanged—with the exception of North America, which has moved up a bit in the weighted version and is now challenging Latin America and the Caribbean for last place. Panel C explains *why* the picture is overall so stable: all regions except North America have very similar infrastructural weights (ranging between 0.60 for Africa and 0.65 for Asia). North America, by contrast, has a much higher weight (0.85). This suggests that nearly all regions have a very similar infrastructural composition, i.e., the same "balanced" mix of small-scale and large-scale transport infrastructure.[18] North America, by contrast, leans more heavily towards large-scale infrastructure, very much in line with the common perception of a car-heavy culture and a lack of pedestrian and cycling infrastructure in this region (Humes, 2016) and empirical evidence that streets in the U.S. are far wider than in any other country.[19] But since North America contains just one land border in the classification used here (United States-Canada)[20] out of a total 312, we can safely state that overall, the infrastructural composition is very similar worldwide. This reinforces the reliability of our approach, since it implies that the fact that our weights are not backed by empirical traffic-throughput statistics is no major issue: We could downgrade or upgrade specific infrastructure types and the overall comparative picture would remain stable. *Third*, regarding border control, the Middle East, North America, and Eur-

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[16] Based on CoW IGO Dataset version 3.0 (Pevehouse et al., 2020). We use the year 2014 and create a count variable that sums up the total number of IGOs two countries are jointly member (full or associate) of.

[17] Here we follow the idea of a comparative sociology of regional integration (Deutschmann, 2021).

[18] This finding also holds when a more fine-grained scheme of 18 United Nations subregions is applied, as shown in the Supplementary Material.

[19] https://streetwidths.its.ucla.edu/, accessed 27/4/2022.

[20] Mexico is counted as Latin American in the applied classification and sea borders are disregarded.

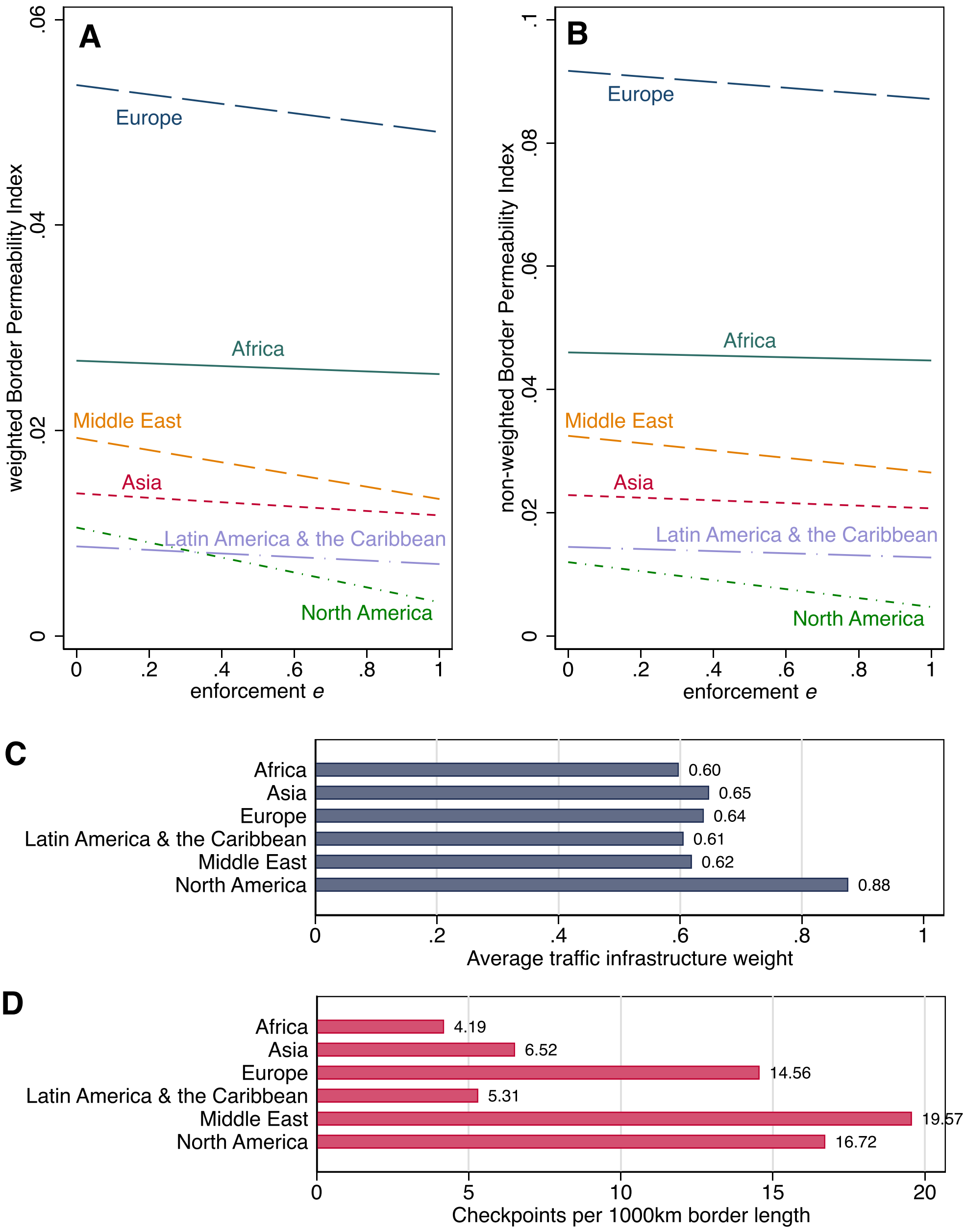

Fig. 3. Cross-regional comparison of BPI, infrastructure composition and checkpoint density. In all panels, the borders a world region contains are weighted by their relative length.

ope feature the highest relative degree of political agency. In these three regions, an increase in enforcement of controls at checkpoints (from $e = 0$ to $e = 1$) has a clear negative impact on the permeability of borders. African border permeability, by contrast, is almost unaffected by increasing enforcement. The reason for this pattern is displayed in Panel D, which shows that the checkpoint density is far higher in the Middle East, North America, and Europe than in Africa, Asia, and Latin America and the Caribbean. It is also noticeable that even at full enforcement, Europe's borders remain far more open than those of other regions. The overall impact of border-control enforcement thus remains limited, at least based on our available data, which could be incomplete (we return to this point in the discussion section).

Next, we can disaggregate the results further and move down to the *nation-state level*. The map in Fig. 4A shows the national averages in border permeability.[21] Countries in Western and Central Europe, East and West Africa, as well as parts of South-East Asia stand out as most permeable. Interestingly, the groups of African countries with high permeability seem aligned to free movement areas on the continent (for an according map, cf. Okunade, 2021). Disaggregating further, the next two panels show the distribution of the BPI at the individual *border level*. Fig. 4B shows that the distribution is highly skewed, resembling a heavy-tailed power-law

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[21] Note that this map, as well as all other panels in Fig. 4, is based on e=0, but the picture looks almost identical for alternative specifications regarding enforcement or weighting (cf. Supplementary Material).

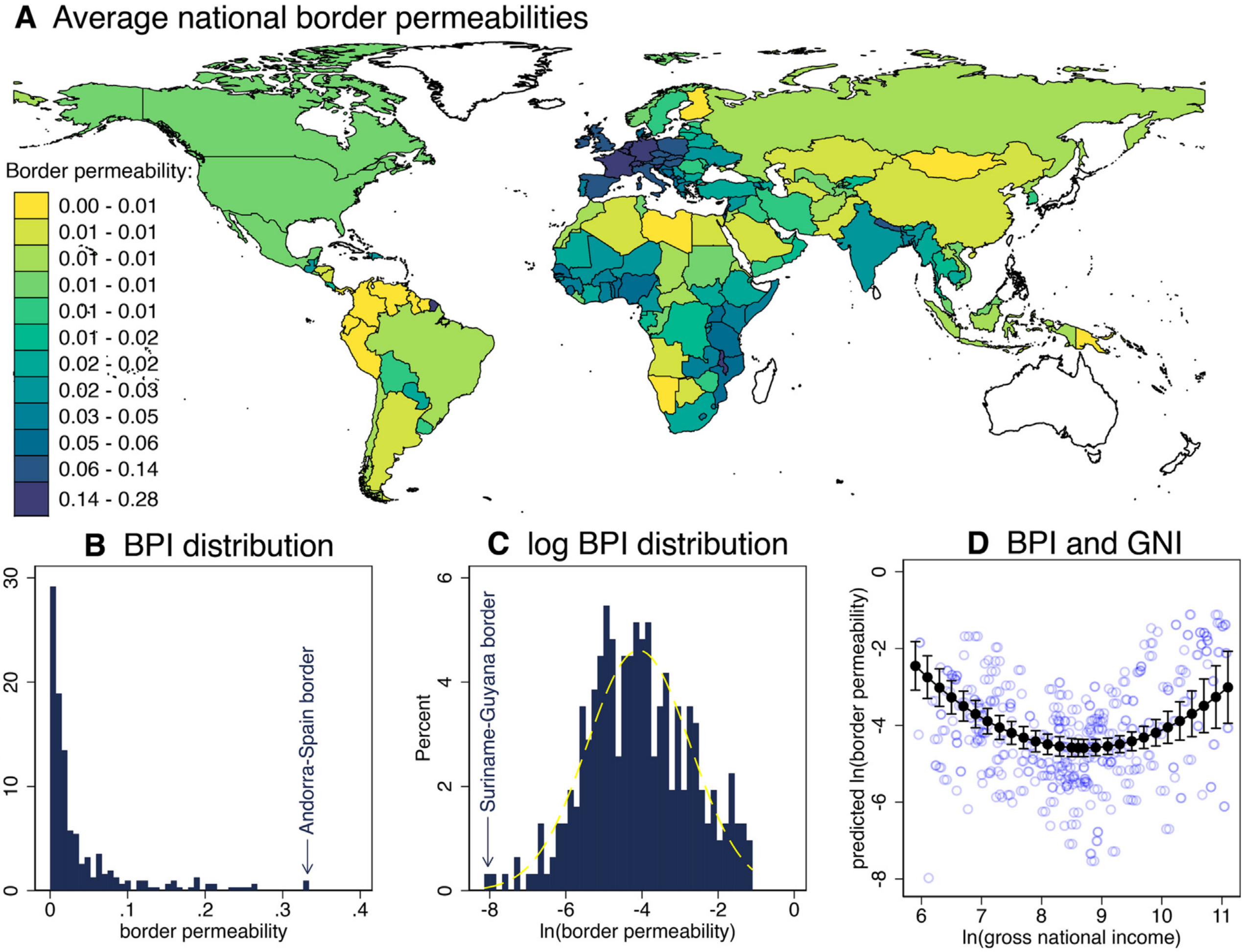

Fig. 4. Global comparisons of border permeability. All graphs based on weighted BPI with $e = 0$. **A** shows the average border permeability of each country, weighting its borders by their length. **B** distribution of border permeability across nation-state borders globally. **C** the same distribution in logarithmic form. **D** Predicted border permeability by economic development (log mean gross national income of the two countries involved), based on full model in Table 2. 95 % confidence intervals are shown, raw observations are depicted as blue circles. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

pattern. The vast majority of borders feature relatively low permeabilities, but a small number of borders are highly permeable. Fig. 4C shows the same distribution in logarithmic format, which is almost normally distributed after this transformation. Table 1 provides an overview of the two tails of this dispersion, i.e., the 20 most and least permeable borders worldwide, for no and full checkpoint enforcement. Regardless of the degree of checkpoint enforcement, the top 20 is dominated by European borders that often involve one small partner, with Spain-Andorra, Slovenia-Austria, and Luxembourg-France constituting the Top 3. The Malawi-Zambia and Malawi-Mozambique borders are among the intra-African borders that appear among the 20 most permeable borders worldwide. In line with this finding, case studies reveal that inhabitants of the Zambia-Malawi-Mozambique borderlands do indeed regard cross-border activity as "normal" and "engage in cross-border activities out of necessity, convenience, for survival, and as practices which they, being inhabitants of the borderlands, have traditionally followed" (Nshimbi, 2019: 47).

A particularly interesting case is the border between Israel and the Palestinian Territories, the 11th most permeable border worldwide if checkpoints are disregarded. When checkpoint controls are fully enforced, its permeability is cut in half (from $\text{BPI}_{e=0} = 0.209$ to $\text{BPI}_{e=1} = 0.099$), but it only drops to rank 32 (cf. complete list in the Supplementary Material) and thus remains quite infrastructurally permeable in global comparison. This is surprising given "the establishment of an elaborate checkpoint system" that creates a situation where "[f]or most inhabitants of the West Bank, passing through an Israeli checkpoint is a daily ritual they cannot avoid" (Rijke, 2021: 1586). The comparatively high permeability also occurs despite the fact that, as mentioned above, we expanded the checkpoint data in this case through an additional comprehensive and, in our view, trustworthy source (B'Tselem, 2021). A possible explanation for this unexpectedly high permeability is that *temporary* and *unannounced* checkpoints set up by the Israeli army—so-called "flying checkpoints" (Forat, 2020)—are omitted from the data. Political and military capacity to shut down the manifold cross-border infrastructure along the densely populated Westbank and Gaza borders (contained as one border in our dataset) with their many daily commuters could thus be higher than it appears based on our analysis.[22]

At the bottom end, the least permeable borders tend to involve areas with low human settlement density and lots of natural obstacles to transport and mobility, such as rainforest (e.g., Venezuela-

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[22] This applies also to other well-guarded borders with mobile surveillance, which remains invisible in this analysis. Another prominent example is the USA-Mexican border, where the U.S. agency that patrols the border has the legal possibility of warrantless stops within the 100-mile border zone (ACLU 2022).

Table 1
The 20 most and least permeable borders worldwide, given no or full checkpoint enforcement.

	Ranked by weighted BPI with $e = 0$			Ranked by weighted BPI with $e = 1$		
Rank	Country 1	Country 2	BPI	Country 1	Country 2	BPI
1	Spain	Andorra	0.334	Luxembourg	France	0.332
2	Luxembourg	France	0.332	Spain	Andorra	0.328
3	Slovenia	Austria	0.327	Slovenia	Austria	0.316
4	Liechtenstein	Austria	0.264	Luxembourg	Belgium	0.263
5	Luxembourg	Belgium	0.263	Liechtenstein	Austria	0.260
6	Switzerland	Germany	0.252	Slovenia	Italy	0.247
7	Slovenia	Italy	0.252	Switzerland	Germany	0.233
8	Switzerland	France	0.242	Switzerland	France	0.232
9	Slovakia	Czechia	0.230	Slovakia	Czechia	0.230
10	Spain	Morocco	0.212	France	Belgium	0.206
11	Palestinian Territ.	Israel	0.209	Germany	Belgium	0.203
12	France	Belgium	0.206	Spain	France	0.192
13	Germany	Belgium	0.203	Netherlands	Belgium	0.187
14	Spain	France	0.193	Malawi	Zambia	0.185
15	Netherlands	Belgium	0.187	Senegal	The Gambia	0.184
16	Malawi	Zambia	0.186	Switzerland	Liechtenstein	0.179
17	Senegal	The Gambia	0.186	Netherlands	Germany	0.165
18	Switzerland	Liechtenstein	0.179	Spain	Morocco	0.164
19	Netherlands	Germany	0.166	Malawi	Mozambique	0.157
20	Malawi	Mozambique	0.158	Slovenia	Hungary	0.154
...	...	...	...	...	...	...
293	Russia	Mongolia	0.002	Uruguay	Argentina	0.000
294	Finland	Norway	0.002	Panama	Colombia	0.000
295	Rwanda	Tanzania	0.002	Suriname	Guyana	0.000
296	Russia	China	0.002	Pakistan	China	0.000
297	Papua New Guinea	Indonesia	0.002	Argentina	Brazil	0.000
298	Pakistan	China	0.002	France	Brazil	−0.001
299	Venezuela	Brazil	0.002	United States	Mexico	−0.001
300	Saudi Arabia	Iraq	0.002	Turkey	Greece	−0.001
301	South Sudan	Ethiopia	0.001	Saudi Arabia	Kuwait	−0.002
302	Kyrgyzstan	China	0.001	Kuwait	Iraq	−0.002
303	Sudan	Libya	0.001	Rwanda	Tanzania	−0.002
304	France	Brazil	0.001	East Timor	Indonesia	−0.002
305	Peru	Brazil	0.001	Lithuania	Belarus	−0.002
306	Brazil	Colombia	0.001	Thailand	Malaysia	−0.002
307	Panama	Colombia	0.001	Romania	Bulgaria	−0.003
308	Guyana	Brazil	0.001	Romania	Serbia	−0.003
309	Suriname	Brazil	0.001	Saudi Arabia	UAE	−0.003
310	DR Congo	CAR	0.000	Zambia	Zimbabwe	−0.006
311	Venezuela	Guyana	0.000	Uzbekistan	Afghanistan	−0.008
312	Suriname	Guyana	0.000	Iraq	Jordan	−0.009

Note: Full list of all 312 borders available in the Supplementary Material. For an explanation for the existence of negative values at the bottom end of the list with full enforcement, cf. footnote 4. CAR = Central African Republic, UAE = United Arab Emirates.

Guyana, Democratic Republic of the Congo-Central African Republic, Suriname-Brazil, Papua New Guinea-Indonesia) and deserts/ arid land (Sudan-Libya, Iraq-Jordan, Saudi Arabia-Kuwait). Such naturally impermeable borders have been described as "Marches borders" in the literature (Ballif and Rosière, 2009; Rosière & Jones 2012: 233). Strict border regimes, political tensions and wealth gaps also appear to play a role, as becomes clear when enforcement is set high (right-hand side of Table 1; e.g., Turkey-Greece, United States-Mexico). Yet, these factors seem secondary compared to the influence of low human settlement density and rough geographic terrain. To explore the explanatory role of such structural factors more systematically, we now look at a series of regression models.

5.2. Explaining the permeability of borders worldwide

To test more thoroughly which factors explain the permeability of borders worldwide, a series of regression models were developed (Table 2). Model 1 shows that, as one could expect from the descriptive findings (in particular Fig. 4A), there is indeed a U-shaped curvilinear relationship between economic development and border permeability: Permeability is highest when the border connects two very rich *or* two very poor countries, but it is lower when the two countries involved have an intermediate GNI. Border permeability also seems to be lower when there is a large income gap between the two countries, but this effect is much weaker and not highly significant.

Model 2 examines the role of political factors and finds that, when examined in isolation, two of the effects go in the expected directions: more democratic countries have more permeable borders and increased international cooperation through joint IGO memberships also appears to lead to higher border permeability (note that these effects will not remain significant in the full model). The political ideology of the countries' leaders in the past decades does not appear to have a measurable impact on border permeability, at least based on the indicator used.[23]

Model 3 tests the influence of mobility-related factors. Notably, there is a strong effect of built-up area density: The more densely built-up the border area is, the more permeable it is, which is in line with our expectation. The population density in the border area has a significant effect of its own, at least in this specification. Thus, the more humans live in the borderlands, the more perme-

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[23] This non-finding also holds when checkpoint enforcement is set to e=1.

Table 2
OLS regression predicting border permeability (log, weighted BPI, e = 0).

	(1) Economics	(2) Politics	(3) Mobility	(4) Culture	(5) Full
GNI (mean, log)	-5.790^{***}				-4.546^{***}
	(0.864)				(0.903)
GNI (mean, log) squared	6.075^{***}				4.530^{***}
	(0.052)				(0.055)
GNI gap (in 1000$)	-0.180^{*}				−0.114
	(0.011)				(0.010)
EIU democracy index (mean)		0.222^{**}			0.101
		(0.006)			(0.006)
% years of rightist heads of government (mean)		−0.043			
		(0.003)			
Joint IGO memberships		0.184^{*}			−0.033
		(0.007)			(0.007)
GHS built-up area density			0.305^{***}		0.177^{*}
			(0.037)		(0.049)
GHS population density			0.165^{*}		0.141^{*}
			(0.001)		(0.001)
GMP mobility (log)			0.112^{*}		0.204^{**}
			(0.024)		(0.035)
GMP tourist-visa cost			-0.124^{**}		-0.072^{*}
			(0.002)		(0.002)
Common spoken language				0.055	
				(0.253)	
Religious proximity (dyad)				0.026	
				(0.290)	
Border length (in 100 km)					-0.180^{***}
					(0.004)
N	452	542	511	479	401
Adjusted R^2	0.22	0.13	0.24	0.00	0.41

Note: Standardized beta coefficients; dyad-clustered standard errors in parentheses; based on cluster diameter of 500 meters for both infrastructure and checkpoints and random-pick approach in clusters. † $p < 0.1$, * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

able the border, which is reasonable. The effect of the more concrete mobility indicator (that is, estimated transnational trips based on GMP data) is also significant and goes into the expected positive direction. Higher visa costs appear to go hand in hand with lower permeability, although this effect is not strong compared to others and becomes insignificant in alternative specifications (cf. Supplementary Material).

Model 4 tests the effect of two cultural variables, common spoken language and religious proximity, which are not significant and contribute nothing to explaining border permeability globally (R^2 = 0). Note, though, that our models only measure the *statistical* strength of average effects; a non-significant overall result does not necessarily preclude the possibility that, in *individual* cases, cultural proximity could have an effect on the permeability of a specific border.

Finally, the full model includes all variables that had a significant effect in the previous models plus the border-length control variable, which has a significant effect of its own, going in the expected direction: The longer the border, the lower its permeability. The full model (and the comparison of the adjusted R^2's across models) reveals a clear picture. Culture and politics play at best minor roles in explaining border permeability globally. What *really* matters is just two factors: the presence of humans (measured here via settlement and population density in the borderlands as well as cross-border trips) and economic development of the two countries. The effect of the latter factor is far greater than that of the former and it takes the (perhaps counter-intuitive) form of a U-shaped relation. Fig. 4D presents this key finding graphically, showing the predicted relationship (based on the full model) for the complete range of empirical observations (visible in the back as blue circles). The U-shaped relation is remarkably clear: Borders of very rich and very poor countries are highly permeable while those of moderately prosperous nation-states are significantly harder to cross, on average.

This main result—economic development being the main predictor of border permeability—was established here using the weighted BPI with e = 0 as the dependent variable, but the same picture emerges consistently for any other degree of checkpoint enforcement (cf. Appendix Table A3). Interestingly, however, the predictive power of the human mobility factor (settlement and population density, mobility, tourist-visa costs) consecutively decreases as enforcement at checkpoints is set higher. Such a decline in explanatory power seems plausible, though, since the presence of humans is directly linked to demand for transport infrastructure, but not necessarily for checkpoints that restrict mobility options. A very similar picture emerges for the non-weighted version of the index (cf. Supplementary Material).

6. Summary and discussion

Based on a new theoretical approach and an original dataset gathered from large-scale digital-trace data, this article examined the permeability of nation-state borders globally. The main contributions can be summarized as follows:

1. Rather than looking at border fortification (walls, fences, etc.) or the shifting legal dimension of borders as previous research has typically done, the theoretical innovation of this article is a focus on transnational transport infrastructure (together with checkpoints) as a material artifact that contains valuable information on border permeability.
2. The empirical application of this new perspective reveals that Europe and parts of Africa have the most, and the Americas the least, permeable borders worldwide.
3. Economic development is by far the most relevant explanatory factor and has a curvilinear relationship with border permeability: Borders of very rich and very poor countries are highly permeable while those of moderately prosperous nation-states are significantly harder to cross.

The exceptionally high permeability of borders in Europe is in line with the self-conception of the region as a pioneer of free movement, with the internally unobstructed flow of both goods and people constituting two of the foundational freedoms of regional integration on the continent (cf. Recchi, 2015; Delhey et al., 2020). What may perhaps be more surprising, at least against the backdrop of the many statistics—from income to literacy to child mortality—that tend to have European countries on one end of the distribution and African countries at the other end, is the almost equally high border permeability in parts of Africa (particularly Western and Eastern Africa), far ahead of the Middle East, Asia, Latin America and the Caribbean, and North America. The regression analyses confirmed that there is no linear relation between prosperity and border permeability. Rather, the relation is U-shaped with some of the poorest regions and some of the richest regions seeing the highest border permeabilities worldwide. What could possibly explain this unique and perhaps unexpected pattern?

To find answers, let us dissect the global income distribution into three groups (rich, poor, and intermediate) and try to find underlying mechanisms for each. For *rich countries*, high border permeability makes sense because (a) they tend to have abundant resources to build transport infrastructure, (b) their economies are often based on free trade and open markets and, since they are in powerful positions regarding terms of trade, they have little to lose from open borders, and (c) free movement and (transnational) mobility becomes an important social value as societies grow rich and postmaterialist (cf. Deutschmann & Recchi, 2022: 292). Citizens of these countries *want* to be mobile and good transport infrastructure allows them to achieve this goal.

For borders between *poor countries*, entirely different mechanisms might be at work. Here, a possible explanation for the high permeability is that (a) these borders often originated as artificial constructs by external colonial forces and (b) resourceless countries still have low state capacity today and thus do not have the same effective power to control the outskirts of their territories. Particularly in Africa, borders were often drawn by colonial powers, disregarding the fact that they cut across the geographies of socially meaningful ethnic communities (Nugent & Asiwaju, 1996; Baud & Van Schendel, 1997). Thus, there was frequent mobility and exchange even before these borders existed. Furthermore, at low state capacity (with little resources available to central governments), there is no political force that could aim to "channel" mobility through a small number of gateways that could then be politically controlled. Mobility can instead occur unimpeded across a border that remains non-reified. Such a situation could lead to a dense network of "naturally grown" (rather than centrally planned) paths and roads. Borders are initially only a *mental image* of central-state (or colonial) elites (Baud & Van Schendel, 1997: 211; Paasi et al., 2022). If these elites don't possess material means (or lack the political will) to enforce them, these borders remain "imagined" and thus continue to have little practical impact on the movements of local people and their commodities in borderlands. A priority of governments in poor countries might also be to protect themselves from the risk of internal revolts and to support domestic infrastructure rather than waste limited resources on policing innocuous inflows at external borders. If borders are "markers of the actual power that states wielded over their own societies" (Baud & Van Schendel, 1997: 215), then states with little economic power and low state capacity will not be able to enforce a non-permeability of borders. Furthermore, local economic cross-border exchange in a borderland may remain particularly important where the government is unable to integrate the border economy into the larger national economy (Ibid.: 229). These arguments are in line with the aforementioned case study from the Zambia–Malawi–Mozambique borderlands, where respondents have traditionally engaged in plentiful cross-border exchange, including out of economic necessity (Nshimbi, 2019). Already in 1997, Baud & Van Schendel argued about the African case, perfectly in line with our findings:

> "Cross-border ethnic, economic, and political ties have remained important, resulting in high levels of interaction between peoples and goods on either side of most African borders. This may be interpreted as the survival of ancient networks of regional trade and a form of protest against a predatory postcolonial state. [...] Intensive cross-border contact is a distinct characteristic of African borderlands. Ieaun Griffiths even suggests that African borders are specifically characterized by their permeability" (p. 239–240)

Twenty-five years later, novel computational means to extract large-scale digital data allowed us to quantify and confirm this particular characteristic of African borders in comparison with all other nation-state borders globally.

Country pairs of *intermediate prosperity* likely find themselves in a different position. Here there are fewer resources available to build transport infrastructure than in rich countries. These countries are also usually less embedded in global trade networks,[24] and social values and personal incomes often leave less room for transnational mobility (cf. Recchi et al., 2019: 17). At the same time, however, their borders are more reified as state capacity is higher than in poor countries, providing more control over territory. *Combined* intermediate prosperity can also occur when a rich state borders a poor state. In these cases, there are additional reasons for lower permeability, including the richer state's interest in reducing the influx of migrants and in avoiding tax losses due to cross-border consumption. This is just a preliminary overview of potential mechanisms behind the U-shaped relation between national income and border permeability. Future research may examine their explanatory power further.

Beyond this main finding, the low impact of border checkpoints on border permeability—even when enforcement is set to its maximum—merits discussion. One possible explanation is that neither OSM nor WFP, our two main sources on checkpoints, features a complete coverage globally. This was visible in the case of Israel and the Palestinian Territories, where the additional source that was implemented (B'Tselem, 2021) contained a much higher number of checkpoints. Yet, even when these additional checkpoints were added, permeability remained relatively high in this case, which is known for being checkpoint-heavy. This could be because *temporary* checkpoints, which can always be set up occasionally, are hard, if not impossible, to capture on a global scale. We already mentioned Israel's

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[24] Visible, e.g., in lower rankings in the KOF Globalization Index, cf. https://kof.ethz.ch/en/forecasts-and-indicators/indicators/kof-globalisation-index.html, accessed 6/5/2022.

"flying checkpoints" above, but there are many other examples: In 2019, for instance, the Venezuelan army needed little more than a couple of containers to completely block the Tienditas bridge at the border with Colombia (Wamsley, 2019). In the U. S., warrantless vehicle searches within the 100-mile border zone are well-documented (ACLU, 2022). And in Europe's Schengen area, internal border controls can be temporarily reinstated in "exceptional situations" such as the COVID-19 pandemic.[25] Another aspect is that controls that occur further inland by officials on moving trains, or even before departure in the country of origin (a point that the shifting-borders paradigm emphasizes), could not be considered here. All this points to the fact that border controls are hard to cover comprehensively due to their partly fluid, volatile, and sometimes "placeless" nature. Political and military control over cross-border traffic infrastructure may thus actually be higher than it may seem based on our analyses. While we were able to perform extensive manual checks to find missing road and railway infrastructure,[26] this was not possible for checkpoints (which are much harder to detect visually with certainty on maps and satellite imagery). Our analysis (and the resulting Border Permeability Dataset) should thus be regarded primarily as a measure of *transport-infrastructural* border permeability with some reservations about the completeness of the political control component.

Having said that, there still likely is a substantial truth to the low impact of checkpoint enforcement: The more border-crossing transport infrastructure there is, the harder it is to shut it down completely. After all, the impossibility to block the countless border-crossings in Europe has been used repeatedly in the Corona pandemic as an argument (or excuse, depending on standpoints) against no-COVID strategies. We are "not Australia, not an island" (Horton, 2021: 359) was a heavily repeated point. While such arguments have also been (mis-)used to justify inaction (Ibid.), they certainly also contain a grain of truth in that more transport infrastructure does indeed require more effort to close than fewer entry points into a territory. Europe, with the highest border permeability globally, finds itself in an exposed situation during such crises. Our findings thus also appear highly relevant in the context of debates about a potential beginning era of de-globalization (Irwin, 2020; Antràs, 2021), at least when it comes to the physical mobility of people and goods at land borders worldwide.[27] In any case, the opening of borders through transport infrastructure and the creation of political capacity to shut it down via checkpoint enforcement is always a dialectic process that needs to be treated as such despite all practical difficulties that arise empirically.

We believe that the novel approach presented here may deliver new insights into many social, political, economic, geographic, epidemiological, legal, and cultural aspects of world development. Based on our macro-level analyses, we cannot determine which social groups are treated selectively at borders or which individual traits lead to discriminatory exclusion. However, we *are* able to detect meaningful global patterns that have the potential to enrich further research.[28] For example, the Border Permeability Dataset could be used to examine whether and how border permeability is related to: COVID-19 outbreaks, mobility flows of various kinds (from trade to migration to tourism to virus flows), conflict, war, terrorist incidents, environmental degradation, or ethnic fractionalization (Drazanova, 2020). Many possible relations and their global implications remain to be explored and we hope that our data will prove a valuable resource to enhance our knowledge in these regards.

CRediT authorship contribution statement

Emanuel Deutschmann: Conceptualization, Investigation, Formal analysis, Visualization, Supervision, Project administration, Writing – original draft. **Lorenzo Gabrielli:** Data curation, Methodology, Software. **Ettore Recchi:** Writing – review & editing.

Data availability

The Border Permeability Dataset is publicly available at: https://doi.org/10.5281/zenodo.7457746.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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[25] Cf. https://ec.europa.eu/home-affairs/policies/schengen-borders-and-visa/schengen-area/temporary-reintroduction-border-control_en, accessed 11/4/2022 and Ruiz Benedicto & Brunet (2018: 30). For additional analyses on the Schengen area, see the Supplementary Material.

[26] Another limitation regards the manual checks: due to their very nature, it is difficult to always say with absolute certainty if and where the 500 meter radius that was used in the automated clustering was passed. While constituting a huge improvement over the raw data generated through the automatized computational process (with its own limitations), the manual checks also brought in some unavoidable measurement error.

[27] A further limitation is that we only focused on land borders in this study, disregarding maritime borders, whose fortification has been the focus of other studies (e.g., Rosière & Jones 2012).

[28] By looking at what occurs at the borders between nation-states worldwide, we also contribute to going beyond methodological nationalism (cf. Eigmüller & Vobruba, 2016: 4).

Appendix

Table A1
Road types on OpenStreetMap and their respective weights in this study.

Key	Value	Description	Proposed weight
Roads			
highway	motorway	A restricted access major divided highway, normally with 2 or more running lanes plus emergency hard shoulder. Equivalent to the Freeway, Autobahn, etc.	1
highway	trunk	The most important roads in a country's system that aren't motorways. (Need not necessarily be a divided highway.)	1
highway	primary	The next most important roads in a country's system. (Often link larger towns.)	0.9
highway	secondary	The next most important roads in a country's system. (Often link towns.)	0.8
highway	tertiary	The next most important roads in a country's system. (Often link smaller towns and villages)	0.7
highway	unclassified	The least important through roads in a country's system – i.e. minor roads of a lower classification than tertiary, but which serve a purpose other than access to properties. (Often link villages and hamlets.) The word 'unclassified' is a historical artefact of the UK road system and does not mean that the classification is unknown.	0.6
highway	residential	Roads which serve as an access to housing, without function of connecting settlements. Often lined with housing.	0.6
Link roads			
highway	motorway_link	The link roads (sliproads/ramps) leading to/from a motorway from/to a motorway or lower class highway. Normally with the same motorway restrictions.	1
highway	trunk_link	The link roads (sliproads/ramps) leading to/from a trunk road from/to a trunk road or lower class highway.	1
highway	primary_link	The link roads (sliproads/ramps) leading to/from a primary road from/to a primary road or lower class highway.	0.9
highway	secondary_link	The link roads (sliproads/ramps) leading to/from a secondary road from/to a secondary road or lower class highway.	0.8
highway	tertiary_link	The link roads (sliproads/ramps) leading to/from a tertiary road from/to a tertiary road or lower class highway.	0.7
Special road types			
highway	living_street	For living streets, which are residential streets where pedestrians have legal priority over cars, speeds are kept very low and where children are allowed to play on the street.	0.6
highway	service	For access roads to, or within an industrial estate, camp site, business park, car park etc.	0.5
highway	pedestrian	For roads used mainly/exclusively for pedestrians in shopping and some residential areas which may allow access by motorised vehicles only for very limited periods of the day.	0.5
highway	track	Roads for mostly *agricultural or forestry uses*. To describe the quality of a track, see tracktype=*. Note: Although tracks are often rough with unpaved surfaces, this tag is not describing the quality of a road but its use. Consequently, if you want to tag a general use road, use one of the general highway values instead of track.	0.5
Paths			
highway	footway	For designated footpaths; i.e., mainly/exclusively for pedestrians. This includes walking tracks and gravel paths.	0.5
highway	bridleway	For horse riders.	0.5
highway	steps	For flights of steps (stairs) on footways.	0.5
highway	path	A non-specific path.	0.5
Bicycle			
highway	cycleway	For designated cycleways.	0.5
cycleway	track	A track provides a route that is separated from traffic. In the United States, this term is often used to refer to bike lanes that are separated from lanes for cars by pavement buffers, bollards, parking lanes, and curbs. *Note* that a cycle track may alternatively be drawn as a separate way next to the road which is tagged as highway = cycleway.	0.5
Railway			
railway	narrow_gauge	Narrow-gauge passenger or freight trains. Narrow gauge railways can have mainline railway service like the Rhaetian Railway in Switzerland or can be a small light industrial railway.	1
railway	preserved	A railway running historic trains, usually a tourist attraction.	0.8
railway	rail	Full sized passenger or freight trains in the standard gauge for the country or state.	1
railway	light_rail	A higher-standard tram system, normally in its own right-of-way. Often it connects towns and thus reaches a considerable length (tens of kilometers).	1
railway	tram	One or two carriage rail vehicles, usually sharing motor road, sometimes called "street running"	0.9
Attributes			
tracktype	grade1	Solid. Usually a paved or sealed surface.	0.7
tracktype	grade2	Solid but unpaved. Usually an unpaved track with surface of gravel.	0.6
tracktype	grade3	Mostly solid. Even mixture of hard and soft materials. Almost always an unpaved track.	0.5
tracktype	grade4	Mostly soft. Almost always an unpaved track prominently with soil/sand/grass, but with some hard or compacted materials mixed in.	0.4
tracktype	grade5	Soft. Almost always an unimproved track lacking hard materials, same as surrounding soil.	0.3
Not (yet) usable			
highway	construction	For roads under construction.	0
railway	construction	Railway under construction.	0
railway	abandoned	The course of a former railway which has been abandoned and the track removed. The course is still recognized through embankments, cuttings, tree rows, bridges, tunnels, remaining track ties, building shapes and rolling or straight ways.	0
railway	disused	A section of railway which is no longer used but where the track and infrastructure remains in place. The track is likely overgrown.	0
railway	razed	Demolished rails that are no longer identifiable, e.g. that have been built over-	0

Note: We list only types of traffic infrastructure that occurred at least once as border-crossing infrastructure globally in our dataset. Other (uncommon) types that exist in the full list (available here: https://wiki.openstreetmap.org/wiki/Template:Map_Features:highway), e.g., a 'raceway' used for motor racing, are not listed.

Table A2
Summary statistics of the border-crossing traffic infrastructure.

Class	Type of infrastructure	Min	Max	Mean	Sum	Percent
	Used types					
Road or path or railway	*manual_streetorrail*	0	317	23.70	7,394	24.54
Road	unclassified[a]	0	206	15.06	4,698	15.59
Path	path	0	363	14.47	4,514	14.98
Special road *or* Bicycle	track	0	193	13.81	4,309	14.30
Road	tertiary	0	47	4.13	1,289	4.28
Road	secondary	0	68	3.40	1,062	3.52
Road	residential	0	170	3.27	1,021	3.39
Road	primary	0	82	2.85	889	2.95
Special road	track_grade3	0	56	2.69	838	2.78
Special road	track_grade2	0	55	1.91	595	1.97
Special road	track_grade4	0	67	1.86	579	1.92
Special road	service	0	31	1.71	533	1.77
Railway	rail	0	29	1.67	520	1.73
Road	trunk	0	20	1.25	390	1.29
Special road	track_grade5	0	55	1.13	352	1.17
Path	footway	0	25	0.77	241	0.80
Ferry	*manual_ferry*	0	15	0.71	221	0.73
Special road	track_grade1	0	15	0.62	192	0.64
Bicycle	cycleway	0	66	0.58	182	0.60
	unknown	0	25	0.21	65	0.22
Road	motorway	0	10	0.19	60	0.20
Path	bridleway	0	7	0.06	19	0.06
Special road	living_street	0	4	0.03	10	0.03
Link road	motorway_link	0	4	0.03	10	0.03
Path	steps	0	2	0.03	10	0.03
Railway	narrow_gauge	0	2	0.03	9	0.03
Link road	primary_link	0	4	0.03	9	0.03
Link road	secondary_link	0	4	0.03	9	0.03
Railway	tram	0	6	0.02	7	0.02
Special road	pedestrian	0	1	0.02	6	0.02
Link road	trunk_link	0	2	0.02	5	0.02
Link road	tertiary_link	0	1	0.01	4	0.01
Railway	preserved	0	2	0.01	2	0.01
Railway	light_rail	0	1	0.00	1	0.00
	Unused types					
Railway	abandoned	0	12	0.21	65	0.22
Railway	disused	0	5	0.05	16	0.05
Railway	razed	0	2	0.02	7	0.02
Railway *or* Road	construction	0	2	0.01	3	0.01
	Sum				30,136	

Note: Non-classifiable types of border-crossing traffic infrastructure are in italics. [a] According to OSM, "the word 'unclassified' is a historical artefact of the UK road system and does not mean that the classification is unknown" (see Table A1).

Table A3
OLS regression predicting border permeability (log, weighted BPI) with varying e.

	(1) $e = 0$	(2) $e = 0.25$	(3) $e = 0.5$	(4) $e = 0.75$	(5) $e = 1$
GNI (mean, log)	−4.546***	−4.407***	−4.995***	−4.641***	−3.219***
	(0.903)	(0.952)	(1.000)	(1.117)	(1.602)
GNI (mean, log) squared	4.530***	4.374***	4.976***	4.559***	3.166***
	(0.055)	(0.058)	(0.062)	(0.070)	(0.097)
GNI gap (in 1000$)	−0.114	−0.109	−0.141	−0.111	−0.023
	(0.010)	(0.011)	(0.013)	(0.014)	(0.014)
EIU democracy index (mean)	0.101	0.117	0.080	0.127	−0.012
	(0.006)	(0.007)	(0.007)	(0.009)	(0.013)
Joint IGO memberships	−0.033	−0.014	−0.030	−0.008	0.140
	(0.007)	(0.008)	(0.008)	(0.009)	(0.018)
GHS built-up area density	0.177*	0.176*	0.171*	0.177*	0.070
	(0.049)	(0.051)	(0.054)	(0.058)	(0.064)
GHS population density	0.141*	0.128†	0.123	0.102	0.085
	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)
GMP mobility (log)	0.204**	0.173*	0.183*	0.151†	0.116
	(0.035)	(0.038)	(0.038)	(0.044)	(0.104)
GMP tourist-visa cost	−0.072*	−0.072†	−0.066†	−0.075†	−0.054
	(0.002)	(0.002)	(0.002)	(0.002)	(0.003)
Border length (in 100 km)	−0.180***	−0.159***	−0.177***	−0.165***	−0.101*
	(0.004)	(0.004)	(0.005)	(0.005)	(0.008)
N	401	401	393	387	368
Adjusted R^2	0.41	0.38	0.40	0.38	0.20

Note: Standardized beta coefficients; dyad-clustered standard errors in parentheses; based on cluster diameter of 500 meters for both infrastructure and checkpoints and random-pick approach in clusters; † $p < 0.1$, * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$. The N drops as e increases because more cases reach a BPI ≤ 0, for which the logarithm is undefined. e = enforcement at checkpoints.

Supplementary Material

Supplementary material and replication files to this article can be found online at https://doi.org/10.1016/j.worlddev.2022.106175.

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