Volume xx (200y), Number z, pp. 1–4

Towards a WHAT-WHY-HOW Taxonomy of Trajectories in Visualization Research

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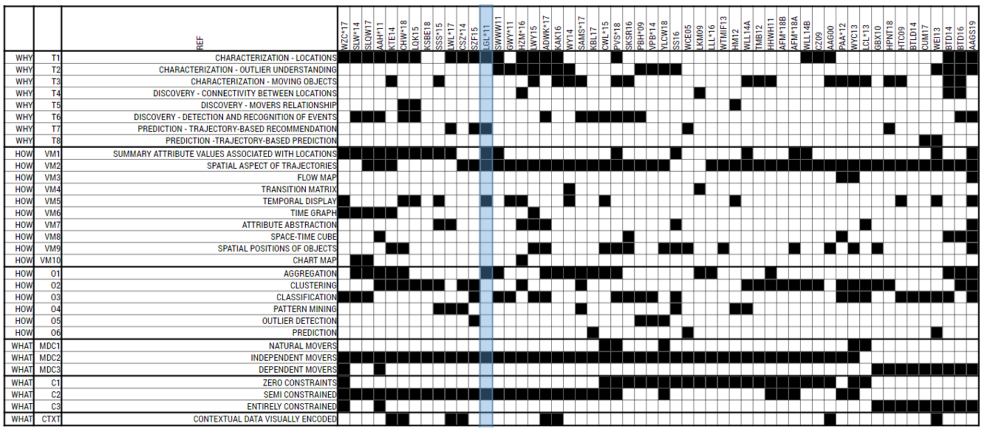

Figure 1: *Our WHAT-WHY-HOW taxonomy of trajectories visualization research illustrated using the Bertifier technique [PDF14]. The documents are ordered through Bertifier's visual similarity algorithm that makes patterns easier to discern. Find the data here:* `https://bit.ly/2vyoSoQ`. *The blue column indicates a document discussed as a populating example here:*`https://bit.ly/3047x5l`

Abstract

Effective analysis of movement often requires a comprehensive approach where computational and visual methods are combined to address a wide variety of tasks involving movers with diverse characteristics. In order to help the process of designing effective methods for a wide range of movement analysis cases, we develop a provisional taxonomy that links what Brehmer et al. [BM13] term statements of WHY-WHAT-HOW with tasks, types of movers, context and methods used to compute or visualize data. Within this document we present the origin of this taxonomy, the process we followed to populate it, discuss the novel categories within it, and finally use it to explore relationships between elements of trajectory analysis. Our main contribution is to provide a new means of connecting elements of WHY-WHAT-HOW when analysing trajectories.

1. Introduction

As capacity to collect data records of movements has increased, many methods and tools have been developed in an effort to analyse movement [AA13]. Brehmer et al. [BM13] introduced a typology that links WHY-WHAT-HOW for the analysis of a field. This model can be used to identify the data, tasks and idioms being employed. It provides "*a scaffold to think systematically about design space*" [BM13] and enables us to develop a taxonomy that may help us learn about current practice, guide analysts and designers and identify gaps for research and design. This document uses the model developed by Brehmer et al. [BM13] to link WHAT-WHY-HOW for the analysis of movement. The result is a taxonomy presented in Figure 1, with 54 documents populating it. Two existing works are relevant to our proposed taxonomy: the conceptual framework by Andrienko et al. [AAB*11] that presents a series of approaches to analyse spatio-temporal data by linking low-level analysis tasks and visualisation methods (WHY-HOW); and the taxonomy developed by Mazimpaka et al. [MT16] that details the types of operations that can be applied to support certain higher-level tasks, provides suggestions for mining methods, and to a lesser extent, visualisation methods (WHY-HOW). Both those papers link tasks and methods to analyse movement and discuss different movers through examples but none attempt to identify mappings between tasks, methods and movers. Their work provides the baseline taxonomy that we build upon. Our scope for movers is the same as theirs, i.e. a mover with a single position, sized at a “human scale”, e.g. natural phenomena, animal, urban, naval and aerial mover. In an effort to understand how types of movers and context impact trajectory analysis, we enlarged the scope of the baseline taxonomy by adding attributes of elements belonging to the WHAT aspect of our taxonomy. We first produced a taxonomy populated by papers selected following a convenience sampling [EMA16] approach in order to find categories which needed modifications. The convenience sample was useful to indicate issues with the categories of the taxonomy, but was neither systematic nor reproducible, thus we restarted populating the taxonomy, following this approach: **(1)** Search on Scopus for all conference papers and journals articles that discuss “trajector(y/ies)”,“visuali(s/z)ation” and exclude keywords that were representative of notions that fell out of our scope, e.g. "trajectories of eye movement". **(2)** Remove posters, short papers and VAST challenges to ensure contributions at a full paper level. **(3)** Remove the papers outside of our scope and use the remaining ones to populate the taxonomy. The categories WHY and HOW within this taxonomy are not described in detail within this work due to their lack of novelty, but further information can be found here: `https://bit.ly/2V7iUWt`. In this document we discuss the elements composing WHAT, reflect upon the resulting taxonomy, and conclude and discuss potential future work.

2. WHAT-WHY-HOW Taxonomy & Reflections

Analysis of visualisation is influenced by knowledge the user possesses about the elements being part of it [MGM19]. Our motivation to develop the attributes composing the elements of WHAT was based on documents mentioning their importance during the analysis of trajectories. One case is Bonham et al. [BNTW18] discussing explanations of vessels trajectories that appear counter-intuitive unless rules they have to abide to and whether they are the ones deciding the trajectories undertaken are known. Another case is Andrienko et el. [AAGS19a] who discuss flight variability and underlines the importance of context such as weather. Brehmer et al. [BM13] acknowledge that “WHAT” comprises a visualisation isn’t agreed upon within the literature and advocate for a “*bring your own what*” mentality. Building upon our baseline taxonomy, we designed the following categories of WHAT:

Mover’s decision capabilities (MDC): The mover’s decision capabilities is a category that indicates whether the mover is the one deciding for the trajectory they follow. The mover’s decision capability is useful to assess if a trajectory is an error, if the mover possessed the ability to take another trajectory, or the existence of potential interactions in between several movers.

MDC1 - Natural movers: this category describes objects where the movement will not undergo modifications due to the will or action of a sentient being, e.g. storms or glaciers. - *MDC2 - Independent movers*: Independent movers are responsible for deciding their own movement, e.g. a pedestrian or a car being driven by an occupant. - *MDC3 - Dependent movers*: Dependent movers are not making the decisions for the movement they are undergoing, e.g. a plane following direction given by an agent outside.

Levels of constraints (C): This section presents categories that define how constrained a mover is, i.e. how many rules the mover has to abide to. This notion is a continuum rather than a series of precisely defined ordered categories, and this notion can also change depending on the context, e.g. a car is semi-constrained, limited normally by legal constraints, but has access to a range of velocities and several directions. It can however be forced into a deviation in various ways: when being towed, or when under instruction by an external person, making it entirely constrained exceptionally.

C1 - Zero constraints: whereby the mover is able to go in any direction within its physical capability so to reach its destination. - *C2 - Semi constrained*: whereby the mover has sets of possibilities for trajectories, but is not free to take all of them. - *C3 - Entirely constrained*: whereby movers are unable to move in ways other than those predefined, e.g. trains are forced to move on rail roads, and are unable to deviate from the planned routes.

Contextual data (CTXT): This category is used to label documents which display contextual data different to movement, e.g. display of metadata of points of interest that can help to understand the reason behind the time a mover stops at a specific location.

Reflecting on the results: Through the development of the taxonomy we made a number of observations, some of which can be seen in the taxonomy table as well, and we reflect on some here. Tasks ‘*Characterisation of locations (T1)*’ and ‘*Characterisation of moving objects (T3)*’ are mainly discussed while using the visualisation method ‘*Spatial aspect of trajectories (Vm2)*’, and most movers are ‘*Independent movers (MDC2)*’, but there is more variety on level of constraints with the task ‘*Characterisation of moving objects (T3)*’ which might indicate this task being researched within more domains, implying more types of movers. Additionally, most cases of ‘*Context (CTXT)*’ are in documents discussing *(T1)*, indicating the usefulness of displaying contextual data for providing richer semantic context. Still, the over-representation of ‘*(MDC2)*’ could indicate a lack of diversity in our population, making the emergence of strong links less likely. Furthermore, all cases of ‘*Entirely constrained (C3)*’ are linked to ‘*Dependent movers (MDC3)*’, potentially indicating combinations of our WHAT elements which are not separable, and thus flaws in our structure.

3. Conclusion

In this poster we introduce a taxonomy that links particular components of WHAT to a WHY-HOW structure of trajectory analysis. The taxonomy is populated with academic papers that involve the visualization of trajectories, and draws links to help navigate the design space in trajectory analysis. In the current form of the taxonomy these links are limited, likely due to particular elements of WHAT being inseparable. Our taxonomy is an in-progress framework that is open for changes to incorporate alternative WHAT structures. Potential modifications could be merging *(MDC)* and *(C)* into one dimension. This dimension would indicate how likely a mover is to follow a trajectory that appears illogical or difficult to interpret, unless provided with information about its intentions or rules it’s abiding to. Additional categories could be physical characteristics of trajectories, e.g. sinuosity, granularity, and attributes of locations, and whether those are constant, e.g. elevation of area, or time-dependent, e.g. precipitation.

References

[AA13] ANDRIENKO N., ANDRIENKO G.: Visual analytics of movement: An overview of methods, tools and procedures. *Information Visualization 12*, 1 (2013). 1

[AAB*11] ANDRIENKO G., ANDRIENKO N., BAK P., KEIM D., KISILEVICH S., WROBEL S.: A conceptual framework and taxonomy of techniques for analyzing movement. *Journal of Visual Languages Computing 22*, 3 (2011). doi:10.1016/j.jvlc.2011.02.003. 1

[AAG00] ANDRIENKO N., ANDRIENKO G., GATALSKY P.: Supporting visual exploration of object movement. In *Proceedings of the working conference on Advanced visual interfaces* (2000), ACM.

[AAGS19a] ANDRIENKO N., ANDRIENKO G., GARCIA J. M. C., SCARLATTI D.: Analysis of flight variability: a systematic approach. *IEEE transactions on visualization and computer graphics 25*, 1 (2019). 2

[AAGS19b] ANDRIENKO N., ANDRIENKO G., GARCIA J. M. C., SCARLATTI D.: Analysis of flight variability: a systematic approach. *IEEE transactions on visualization and computer graphics 25*, 1 (2019).

[AAH*11] ANDRIENKO G., ANDRIENKO N., HURTER C., RINZIVILLO S., WROBEL S.: From movement tracks through events to places: Extracting and characterizing significant places from mobility data. In *2011 IEEE Conference on Visual Analytics Science and Technology (VAST)* (2011), IEEE.

[ADWK*17] AL-DOHUKI S., WU Y., KAMW F., YANG J., LI X., ZHAO Y., YE X., CHEN W., MA C., WANG F.: Semantictraj: A new approach to interacting with massive taxi trajectories. *IEEE transactions on visualization and computer graphics 23*, 1 (2017).

[AFM*18a] AGARWAL P. K., FOX K., MUNAGALA K., NATH A., PAN J., TAYLOR E.: Subtrajectory clustering. *Proceedings of the 35th ACM SIGMOD-SIGACT-SIGAI Symposium on Principles of Database Systems - SIGMOD/PODS 18* (2018). doi:10.1145/3196959.3196972.

[AFM*18b] AGARWAL P. K., FOX K., MUNAGALA K., NATH A., PAN J., TAYLOR E.: Subtrajectory clustering: Models and algorithms. In *Proceedings of the 35th ACM SIGMOD-SIGACT-SIGAI Symposium on Principles of Database Systems* (2018), ACM.

[BM13] BREHMER M., MUNZNER T.: A multi-level typology of abstract visualization tasks. *IEEE Transactions on Visualization and Computer Graphics 19*, 12 (2013). doi:10.1109/tvcg.2013.124. 1, 2

[BNTW18] BONHAM C., NOYVIRT A., TSALAMANIS I., WILLIAMS S.: Analysing port and shipping operations using big data. 2

[BRA*13] BOGORNY V., RENSO C., AQUINO A. R. D., SIQUEIRA F. D. L., ALVARES L. O.: Constant - a conceptual data model for semantic trajectories of moving objects. *Transactions in GIS 18*, 1 (2013). doi:10.1111/tgis.12011.

[BRSW06] BOMBERGER N., RHODES B., SEIBERT M., WAXMAN A.: Associative learning of vessel motion patterns for maritime situation awareness. *2006 9th International Conference on Information Fusion* (2006). doi:10.1109/icif.2006.301661.

[BTD14] BUSCHMANN S., TRAPP M., DOLLNER J.: Real-time animated visualization of massive air-traffic trajectories. *2014 International Conference on Cyberworlds* (2014). doi:10.1109/cw.2014.32.

[BTD16] BUSCHMANN S., TRAPP M., DÖLLNER J.: Animated visualization of spatial–temporal trajectory data for air-traffic analysis. *The Visual Computer 32*, 3 (2016).

[BTLD14] BUSCHMANN S., TRAPP M., LÜHNE P., DÖLLNER J.: Hardware-accelerated attribute mapping for interactive visualization of complex 3d trajectories. In *2014 International Conference on Information Visualization Theory and Applications (IVAPP)* (2014), IEEE.

[CHW*18] CHEN W., HUANG Z., WU F., ZHU M., GUAN H., MACIEJEWSKI R.: Vaud: A visual analysis approach for exploring spatio-temporal urban data. *IEEE transactions on visualization and computer graphics 24*, 9 (2018).

[CSZ*14] CHU D., SHEETS D. A., ZHAO Y., WU Y., YANG J., ZHENG M., CHEN G.: Visualizing hidden themes of taxi movement with semantic transformation. *2014 IEEE Pacific Visualization Symposium* (2014). doi:10.1109/pacificvis.2014.50.

[Cum17] CUMMINGS M.: Automation bias in intelligent time critical decision support systems. *Decision Making in Aviation* (2017). doi:10.4324/9781315095080-17.

[CWL*15] CHEN Y.-C., WANG Y.-S., LIN W.-C., HUANG W.-X., LIN I.-C.: Interactive visual analysis for vehicle detector data. In *Computer Graphics Forum* (2015), vol. 34, Wiley Online Library.

[CZ09] CHANG Â., ZHOU B.: Multi-granularity visualization of trajectory clusters using sub-trajectory clustering. *2009 IEEE International Conference on Data Mining Workshops* (2009). doi:10.1109/icdmw.2009.24.

[EMA16] ETIKAN I., MUSA S. A., ALKASSIM R. S.: Comparison of convenience sampling and purposive sampling. *American journal of theoretical and applied statistics 5*, 1 (2016), 1–4. 2

[GBX10] GÜTING R. H., BEHR T., XU J.: Efficient k-nearest neighbor search on moving object trajectories. *The VLDB JournalâĂŤThe International Journal on Very Large Data Bases 19*, 5 (2010).

[GWY*11] GUO H., WANG Z., YU B., ZHAO H., YUAN X.: Tripvista: Triple perspective visual trajectory analytics and its application on microscopic traffic data at a road intersection. *2011 IEEE Pacific Visualization Symposium* (2011). doi:10.1109/pacificvis.2011.5742386.

[HHBR15] HORNAUER S., HAHN A., BLAICH M., REUTER J.: Trajectory planning with negotiation for maritime collision avoidance. *TransNav, the International Journal on Marine Navigation and Safety of Sea Transportation 9*, 3 (2015). doi:10.12716/1001.09.03.05.

[HHWH11] HÃŰFERLIN M., HÃŰFERLIN B., WEISKOPF D., HEIDEMANN G.: Interactive schematic summaries for exploration of surveillance video. *Proceedings of the 1st ACM International Conference on Multimedia Retrieval - ICMR 11* (2011). doi:10.1145/1991996.1992005.

[HM12] HEUER B. R. H. Z. J., MAUCHER J.: Empirical analysis of passenger trajectories within an urban transport hub.

[HPNT18] HURTER C., PUECHMOREL S., NICOL F., TELEA A.: Functional decomposition for bundled simplification of trail sets. *IEEE transactions on visualization and computer graphics 24*, 1 (2018).

[HTC09] HURTER C., TISSOIRES B., CONVERSY S.: Fromdady: Spreading aircraft trajectories across views to support iterative queries. *IEEE Transactions on Visualization and Computer Graphics 15*, 6 (2009). doi:10.1109/tvcg.2009.145.

[HZM*16] HUANG X., ZHAO Y., MA C., YANG J., YE X., ZHANG C.: Trajgraph: A graph-based visual analytics approach to studying urban network centralities using taxi trajectory data. *IEEE transactions on visualization and computer graphics 22*, 1 (2016).

[KAK16] KOMAMIZU T., AMAGASA T., KITAGAWA H.: Visual spatial-olap for vehicle recorder data on micro-sized electric vehicles. *Proceedings of the 20th International Database Engineering Applications Symposium on - IDEAS 16* (2016). doi:10.1145/2938503.2938532.

[KBL17] KARIM L., BOULMAKOUL A., LBATH A.: Real time analytics of urban congestion trajectories on hadoop-mongodb cloud ecosystem. *Proceedings of the Second International Conference on Internet of things, Data and Cloud Computing - ICC 17* (2017). doi:10.1145/3018896.3018923.

[KSBE18] KRÜGER R., SIMEONOV G., BECK F., ERTL T.: Visual interactive map matching. *IEEE transactions on visualization and computer graphics 24*, 6 (2018).

[KTE14] KRUEGER R., THOM D., ERTL T.: Visual analysis of movement behavior using web data for context enrichment. *2014 IEEE Pacific Visualization Symposium* (2014). doi:10.1109/pacificvis.2014.57.

[Lax08] LAXHAMMAR R.: Anomaly detection for sea surveillance. In *2008 11th international conference on information fusion* (2008), IEEE.

[LCL*13] LU K., CHAUDHURI A., LEE T.-Y., SHEN H.-W., WONG P. C.: Exploring vector fields with distribution-based streamline analysis. *2013 IEEE Pacific Visualization Symposium (PacificVis)* (2013). doi:10.1109/pacificvis.2013.6596153.

[LGL*11] LIU H., GAO Y., LU L., LIU S., QU H., NI L. M.: Visual analysis of route diversity. *2011 IEEE Conference on Visual Analytics Science and Technology (VAST)* (2011). doi:10.1109/vast.2011.6102455.

[LKM09] LIEBIG T., KÃŰRNER C., MAY M.: Fast visual trajectory analysis using spatial bayesian networks. *2009 IEEE International Conference on Data Mining Workshops* (2009). doi:10.1109/icdmw.2009.44.

[LLL*16] LI Y., LIU R. W., LIU J., HUANG Y., HU B., WANG K.: Trajectory compression-guided visualization of spatio-temporal ais vessel density. *2016 8th International Conference on Wireless Communications Signal Processing (WCSP)* (2016). doi:10.1109/wcsp.2016.7752733.

[LQK15] LIU C., QIN K., KANG C.: Exploring time-dependent traffic congestion patterns from taxi trajectory data. *2015 2nd IEEE International Conference on Spatial Data Mining and Geographical Knowledge Services (ICSDM)* (2015). doi:10.1109/icsdm.2015.7298022.

[LWL*17] LIU D., WENG D., LI Y., BAO J., ZHENG Y., QU H., WU Y.: Smartadp: Visual analytics of large-scale taxi trajectories for selecting billboard locations. *IEEE transactions on visualization and computer graphics 23*, 1 (2017).

[LWY15] LU M., WANG Z., YUAN X.: Trajrank: Exploring travel behaviour on a route by trajectory ranking. *2015 IEEE Pacific Visualization Symposium (PacificVis)* (2015). doi:10.1109/pacificvis.2015.7156392.

[MGM19] MCCURDY N., GERDES J., MEYER M.: A framework for externalizing implicit error using visualization. *IEEE transactions on visualization and computer graphics 25*, 1 (2019). 2

[MT16] MAZIMPAKA J. D., TIMPF S.: Trajectory data mining: A review of methods and applications. *Journal of Spatial Information Science*, 13 (2016). doi:10.5311/josis.2016.13.263. 1

[PAA*12] PELEKIS N., ANDRIENKO G., ANDRIENKO N., KOPANAKIS I., MARKETOS G., THEODORIDIS Y.: Visually exploring movement data via similarity-based analysis. *Journal of Intelligent Information Systems 38*, 2 (2012).

[PBH*09] PATEL D., BHATT C., HSU W., LEE M. L., KANKANHALLI M.: Analyzing abnormal events from spatio-temporal trajectories. *2009 IEEE International Conference on Data Mining Workshops* (2009). doi:10.1109/icdmw.2009.45.

[PDF14] PERIN C., DRAGICEVIC P., FEKETE J.-D.: Bertifier: New interactions for crafting tabular visualizations. In *IHM'14, 26e conférence francophone sur l'Interaction Homme-Machine* (2014). 1

[PVS*18] PERIN C., VUILLEMOT R., STOLPER C., STASKO J., WOOD J., CARPENDALE S.: State of the art of sports data visualization. In *Computer Graphics Forum* (2018), vol. 37, Wiley Online Library.

[SAMS*17] SACHA D., AL-MASOUDI F., STEIN M., SCHRECK T., KEIM D. A., ANDRIENKO G., JANETZKO H.: Dynamic visual abstraction of soccer movement. In *Computer Graphics Forum* (2017), vol. 36, Wiley Online Library.

[SKSR16] SAILER C., KIEFER P., SCHITO J., RAUBAL M.: Map-based visual analytics of moving learners. *International Journal of Mobile Human Computer Interaction (IJMHCI) 8*, 4 (2016).

[SLQW17] SUN G., LIANG R., QU H., WU Y.: Embedding spatio-temporal information into maps by route-zooming. *IEEE transactions on visualization and computer graphics 23*, 5 (2017).

[SLW*14] SUN G., LIU Y., WU W., LIANG R., QU H.: Embedding temporal display into maps for occlusion-free visualization of spatio-temporal data. *2014 IEEE Pacific Visualization Symposium* (2014). doi:10.1109/pacificvis.2014.56.

[SS16] SITARAM D., SUBRAMANIAM K. V.: Complex event processing in big data systems. *Big Data Analytics* (2016). doi:10.1007/978-81-322-3628-3_8.

[SSS*15] SPRETKE D., STEIN M., SHARALIEVA L., WARTA A., LICHT V., SCHRECK T., KEIM D. A.: Visual analysis of car fleet trajectories to find representative routes for automotive research. *2015 19th International Conference on Information Visualisation* (2015). doi:10.1109/iv.2015.63.

[SWWW11] SCHEEPENS R., WILLEMS N., WETERING H. V. D., WIJK J. J. V.: Interactive visualization of multivariate trajectory data with density maps. *2011 IEEE Pacific Visualization Symposium* (2011). doi:10.1109/pacificvis.2011.5742384.

[SZF15] SHEN Y., ZHAO L., FAN J.: Analysis and visualization for hot spot based route recommendation using short-dated taxi gps traces. *Information 6*, 2 (2015).

[TMB12] TAHIR A., MCARDLE G., BERTOLOTTO M.: Identifying specific spatial tasks through clustering and geovisual analysis. *2012 20th International Conference on Geoinformatics* (2012). doi:10.1109/geoinformatics.2012.6270301.

[VPB*14] VASENEV A., PRADHANANGA N., BIJLEVELD F., IONITA D., HARTMANN T., TEIZER J., DORÃĽE A.: An information fusion approach for filtering gnss data sets collected during construction operations. *Advanced Engineering Informatics 28*, 4 (2014). doi:10.1016/j.aei.2014.07.001.

[WCE05] WAN T. R., CHEN T., EARNSHAW R. A.: A motion constrained dynamic path planning algorithm for multi-agent simulations.

[Wei13] WEITZ P.: Determination and visualization of uncertainties in 4d-trajectory prediction. *2013 Integrated Communications, Navigation and Surveillance Conference (ICNS)* (2013). doi:10.1109/icnsurv.2013.6548525.

[WLL14a] WANG Y., LEE K., LEE I.: Directional higher order information for spatio-temporal trajectory dataset. *2014 IEEE International Conference on Data Mining Workshop* (2014). doi:10.1109/icdmw.2014.48.

[WLL14b] WANG Y., LEE K., LEE I.: Visual analytics of topological higher order information for emergency management based on tourism trajectory datasets. *Procedia Computer Science 29* (2014).

[WTMIF13] WAGA K., TABARCEA A., MARIESCU-ISTODOR R., FRÄNTI P.: Real time access to multiple gps tracks. In *WEBIST* (2013).

[WY14] WANG Z., YUAN X.: Urban trajectory timeline visualization. *2014 International Conference on Big Data and Smart Computing (BIGCOMP)* (2014). doi:10.1109/bigcomp.2014.6741397.

[WYC13] WU H.-R., YEH M.-Y., CHEN M.-S.: Profiling moving objects by dividing and clustering trajectories spatiotemporally. *IEEE Transactions on Knowledge and Data Engineering 25*, 11 (2013).

[WZC*17] WU W., ZHENG Y., CAO N., ZENG H., NI B., QU H., NI L. M.: Mobiseg: Interactive region segmentation using heterogeneous mobility data. *2017 IEEE Pacific Visualization Symposium (PacificVis)* (2017). doi:10.1109/pacificvis.2017.8031583.

[YLCW18] YU Q., LUO Y., CHEN C., WANG X.: Trajectory outlier detection approach based on common slices sub-sequence. *Applied Intelligence 48*, 9 (2018).