Judges' Commentary: Out of Gas and Driving on E (for Electricity, not Empty)

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Introduction

The 2018 ICM Network Science / Operations Research Question, Problem D, asked students to explore the transition from fuel-burning vehicles to electric vehicles by studying the current growth and evolution of charging networks and proposing further growth of the network. Teams were also asked to analyze how their proposed model(s) were impacted by the varying geographies of a diverse set of nations.

In alignment with the goals of the ICM, this problem required teams to pull from a diverse set of skills, not only to perform a meaningful analysis, but also to draw clear and convincing connections from the inputs, the outputs, and the very structure of their model to the real world issues surrounding migration to electric vehicles.

In addition to presenting a 20-page report, each team was asked to submit a one-page handout for national leaders attending an energy summit;

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this challenged teams to take a step away from the technical details of their analysis and practice the important skill of making their findings relevant to a nontechnical audience.

Judges' Criteria

As with all ICM problems, this problem was intentionally left open for broad interpretation, and this openness resulted in a wide variety of approaches. Also, as with all ICM problems, there is no one right answer—and even the best solutions have room for improvement in at least one area. Our international panel of final judges included engineers, applied mathematicians, statisticians, and network scientists from business, academia, and government, who were looking for papers whose ideas were innovative and whose clear writing convinced them that the methodologies and findings were sound.

Overall, the judges were impressed, but there were some areas of concern. In the sections below, we offer commentary on the components of the problem and offer strong examples from this year's submissions.

Citations, References, and Cheating

ICM problems are inherently hard, because if we knew the answers, we would not bother to ask the questions. However, the problems posed by the ICM are often pressing and real challenges facing the world, which means that many smart people have already started thinking about these problems.

Therefore, while we do see some really innovative ideas that have no origin in the existing literature, many strong teams start their work with a thorough literature review to see what ideas have already been tried and how they can leverage existing work. This approach of using sources to improve the final product goes beyond the technical, as many teams are able to strengthen their background and motivation statements by finding and citing credible sources as opposed to making their own assertions. While the ICM does not force the use of any particular citation standard (e.g., APA or Chicago), teams should do their best to use citations wherever applicable. It is important to note that this need to cite applies also to images or tables from online sources.

This year, most papers from Problem D did not include a strong set of references. Furthermore, due to possible cheating, this year, 376 ICM teams (3%) were disqualified; and many more were flagged for potential cheating, either due to similarities among submissions or similarities to sources that were not cited. Flagrant plagiarism is in direct violation of the spirit of the competition, and proper use of citations can help teams avoid a disqualification. The judges encourage teams to use outside sources, cite them

properly, and then build in their own creative ideas to make their solution unique and innovative.

The Summary and Country Leader Handout

All ICM teams must include a one-page summary. Unfortunately, many teams provide an abstract instead, meaning that they do not include their findings. Additionally, many teams use jargon or rely on the name of a technique to convey their methodology.

This year, in addition to providing a one-page summary, ICM teams who chose Problem D also had to write a handout for national leaders attending an energy summit. As with the one-page summary, some teams failed to include the information that a leader would need to make important decisions about moving their country toward an all-electric vehicle fleet. Also, some teams unfortunately mistook this requirement as an opportunity to add insights that were not included in the paper, instead of highlighting the key ideas that were supported by the analysis in their papers.

Both of these requirements, the summary and the handout, required teams to figure out how to synthesize their work and convey it to a particular audience. This is a difficult skill that is not often emphasized in undergraduate programs; however, it is a valuable skill that transcends beyond the college experience. While not every ICM problem has an additional requirement, such as a handout, when included, they can serve as a discriminator.

The Modeling

While there was a wide variety of interesting approaches, the judges were looking for papers in which the teams developed models that could address the following tasks:

- Explore the growth of the existing Tesla charging network in the U.S. Since the Tesla network has been growing for a while, the problem authors believed this would allow teams to develop a model and possibly use the existing data to validate their model. The judges saw such model validations as a strength.
- Determine the optimal end-state of a charging network in either South Korea, Ireland, or Uruguay. The judges were surprised that some teams seemed compelled to create a whole new approach, as they expected teams to simply apply, or possibly extend, their models from the U.S. While many teams' new models did not add value at this phase, there were a few teams who made strong justifications for their country-specific approaches. Overall, the judges were looking for a strong rationale for any models that were created or modifications that were made.

- Explore the evolution of the network from 0% electric vehicles to 100% electric vehicles. This was a very challenging aspect of the problem, and it was interpreted differently by different teams. Some teams focused heavily on exploring consumer-based models for when drivers would want to switch, while other teams focused more on production-based models either of the vehicles themselves or of the resources to build the stations and the demand on the electricity to support those stations. The judges were open to new ideas and interpretations, seeking the papers that best explained their rationales and approaches in clear and convincing ways.
- Understand the flexibility in the proposed model(s) to design the evolving network of charging stations for different nations, with differing geographies and demographics. While the problem listed a variety of countries, it was not the intention of the problem authors that teams would address that exact set of countries. Rather, they provided a list of very diverse nations (small, large, wealthy, poor, densely populated, sparsely populated, contiguous, archipelagic) hoping to trigger teams into identifying key considerations that may drive a nation's decision and timeline for electric vehicle conversion. Ultimately, many teams stuck to this list or even selected only one nation from the list to do another comparison without extrapolating. The judges looked for papers that used this task to identify the strengths and weaknesses in the flexibility of their model, and some teams went above and beyond by creating classifications for nations and developing models for each classification.
- Discuss the impact of future technologies on the findings. Most teams provided a qualitative discussion, although some teams found a way to fold in a quantitative analysis. The purpose of this part of the question was to push teams to think about disruptive technologies and how those could impact all the hard work they had just presented.

The Explanations of the Modeling

No matter how great a model is, if no one understands it, then it will not be adopted or used. Therefore, one of the goals of the ICM is to give students the challenge, not only of developing a model to answer a hard problem, but also to write about that model and their findings in a convincing and clear way.

Additional Discriminators

It is impossible to develop a complete list of the things that cause a judge to move one paper above another. However, an incomplete list includes the following.

- **Assumptions, Rationales, and Revisitations.** Many teams provide a list of assumptions, but only the strongest modelers are able to capture all of their assumptions. Often, teams list assumptions that actually are not reflected in the models; and even more often, teams provide a model that has inherent assumptions that are not listed.

  Simply listing an assumption, even if it is appropriate, is not as strong as justifying it. It is best to include a rationale for each assumption—perhaps it reflects the real world, or perhaps it simplifies the model without overly compromising fidelity. Furthermore, the strongest teams may revisit their assumptions as a sensitivity analysis.

- **Model Assessment and Sensitivity Analysis.** In order to understand the strengths, weaknesses, flexibility, and utility of the model(s), it helps to test the model in a variety of situations. Rather than simply listing only qualitative strengths and weaknesses (e.g., too few or too many inputs, the complexity of calculation, etc.), papers that include well-defined and well-described testing of their model often stand out to the judges.

- **Creativity in Methodology Descriptions and Visualizing Results.** Often, the ideas that are being presented are complex, and it is important to remember that the judges span a diverse set of backgrounds. Therefore, visualizations that assist in our understanding of the process and/or the findings can be beneficial.

Discussion of Outstanding Papers

After much discussion and deliberation by our diverse team of final judges, six papers were selected to receive the distinction of Outstanding. They were from the institutions Beijing University of Technology, Shanghai Jiao Tong University, Tsinghua University, Tianjin Polytechnic University, Xidian University, and Zhejiang Sci-Tech University. Discussions of the six Outstanding papers follow.

Beijing University of Technology, China

The key to any good ICM submission is the culminating executive summary. This team exemplified this effort with an executive summary that addressed all aspects of Problem D on national electric grid infrastructure with clear, concise writing. It provided a good overview of their methods, and very importantly, their numerical results. Their summary addressed the *three key components of an executive summary*:

- a clear definition of the problem,
- an explanation of how they addressed it, and

- a compilation of the main takeaways.

Throughout the paper, the team introduced a good mix of models and ideas and explained them in a clear logical manner. The judges enjoyed the inclusion of the competitive exclusion model, reminiscent of a predator-prey situation, which was also an uncommon approach among the finalists. In the sections where the team gave future projections, rather than just giving one answer to the problem, they coupled this with a range of values to reflect the inherent uncertainty of any prediction.

In Task 3 of Problem D, the teams were asked to consider countries with varying characteristics, such as population density and geography, and to see how their model would apply (or not apply). Most teams selected a subset of the five given countries to consider, and some considered only one of these countries. However, this team went far beyond. First, they expanded their model to include the standard deviation ellipse method, which was a novel technique to quantify whether a country's population distribution is balanced or unbalanced, as shown in **Figure 1**.

Figure 1. Beijing University of Technology: (a) The paper's Figure 8 shows the unbalanced population distribution in Australia. (b) The paper's Figure 10 shows the balanced population distribution in Uruguay.

Then they applied their model not only to the USA, South Korea, and the five listed countries, but they also doubled the number of countries considered, to 10 in total. This leads to a good point of general advice: While teams should read the problem statements as strong suggestions, they should also feel free to expand beyond them, as this team did.

For the final task about future technology's effects on electric cars, compared to other papers, this team gave more advanced considerations to alternative technologies. While the task mentioned specific future possibilities such as self-driving cars, this team went beyond and considered more possibilities, including wireless charging.

Shanghai Jiao Tong University, China: "Design of Charging Network"

This team from Shanghai Jiao Tong University started by giving some background into a previously published work in the area of electric vehicle networks, using a stochastic flow-capturing model (SFCLM). The team also compared the number of electric cars per charging station to that of gasoline and note that there has been an aggressive rollout out charging stations that bodes favorably to the electric vehicles. This background laid a good foundation for the paper. Their assumptions section included reasonable assumptions on when a driver would recharge, and they limited the scope of their work to only public chargers. While this latter assumption seems reasonable and acknowledged privately owned chargers, it would be interesting to know how this assumption affected the modeling. The judges point this out, not as a criticism, but rather to illustrate that no matter how excellent a submission is, there are always more questions to be answered to gain additional insight on a good modeling problem!

To determine placement of charging stations, the team divided the country into urban, suburban, and rural regions. For urban and suburban, they introduced the idea of a minimum radius, inversely proportional to the square root of the geometric average of two estimates of car density: population and GDP. The difference between urban and suburban charging station density was the coefficient of proportionality and was based on data about Manhattan, which is reported in the paper to have a fully-deployed charging station network. This model is refined using a k-means algorithm using an L_1-norm modeling distance on a rectangular urban grid instead of the Euclidean distance, which is less realistic in an urban environment. Unfortunately, the rational for the k-means algorithm or how it is used is never fully explained, and improving this writing would have made this strong paper even stronger. Rural areas were further subdivided into villages and public roads. The team stated that public roads would need a charging station about every 20 miles, and that since villages are small, they only need one charging station. However, it is not clear if these assertions are based on assumption, analysis, or a combination thereof.

Next, the team considered South Korea and divided it into urban, suburban, and rural areas, denoting which areas belong to which categories. At this point, the team discussed more about destination vs. supercharging stations, making the reasonable assertion that the superchargers are on the highways. A Markov model vs. the previous k-means algorithm is used to place the charging stations. This model is compared to the SFCLM mentioned above, with similar results. In fact, one of the strengths of this paper was its clear comparison to existing work as a means of validating the team's approach. A dynamical model of the increase in the number of cars over time was presented with a 90% saturation by 2042. An aggressive roll-out of charging stations was modeled, in order to encourage use.

Another strength of this paper was its discussion of migrating diverse countries to electric vehicles. Their approach included a good qualitative discussion of GDP and Gini coefficients, as well as geography. A combined index was derived based on charger profits and consumption, and applied to China and Indonesia, with the conclusion that electric vehicles are viable in China, but may not be in Indonesia at this point.

The paper concludes with a thoughtful discussion of strengths and weaknesses and a country handout that, while not self contained as intended, did a good job explaining the issues by referring back to the work within the rest of the paper.

Tsinghua University, China: "Forecast, Blueprint, Strategy, for EV's Future"

This team from Tsinghua University developed several models to address the charger-location problem and forecast the growth of electric vehicles in different countries. The team first developed a linear programming model to find the maximal coverage for the charger location problem. Demonstrating resiliency and flexibility in modeling, the team converted the LP model into an equivalent minimum-cost max-flow model after they realized that the large LP model would be computationally difficult to solve with standard algorithms such as the simplex method.

For the location analysis, the team applied a Google Geocode API to transform the raw data into the Geodetic Coordinate System (latitude, longitude) for all the nodes—chargers and cities/clusters. They applied a Nash equilibrium model to develop a market evolution strategy that predicts a pattern in order to decide the weighting between constructing EVs and constructing chargers.

Next, the team developed a Bass diffusion model to predict the growth of electric vehicles, which they applied to the market evolutions of the U.S. and South Korea by fitting the existing sales data into the Bass diffusion model. Finally, to model the market evolution of electric vehicles across the globe for countries with widely varying characteristics, the team developed a multiple linear regression model incorporating a range of variables to include: GDP per capita, producer price Index, Gini coefficients, road network total miles, vehicles per capita, oil price, and a measure of urbanization.

The writing in the paper was very clear, with appropriate reference citations; and even though it includes several disparate models, the paper is coherent and flows between the various tasks and models. The heatmap style figures showing the location of charging stations in the U.S. and Korea, **Figure 2**, were informative and conveyed the results in a visually meaningful way.

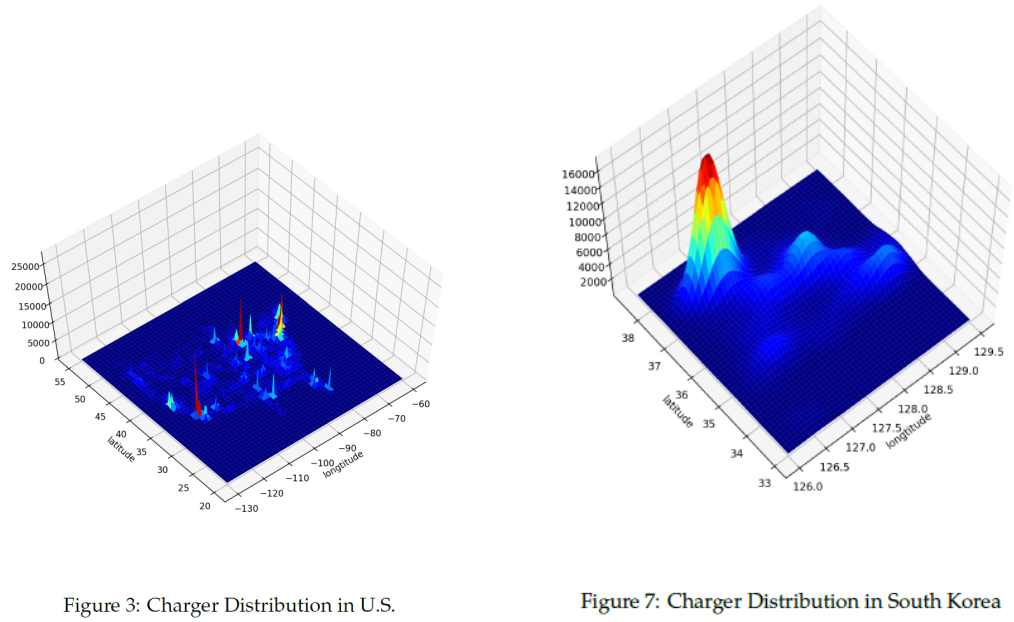

Figure 3: Charger Distribution in U.S.

Figure 7: Charger Distribution in South Korea

Figure 2. Tsinghua University: (a) This paper's Figure 3 shows their proposed charger distribution in the U.S. (b) The paper's Figure 7 shows their proposed charger distribution in South Korea.

This strong submission could have been further improved by having the handout for the country leaders summarize the findings, rather than introducing new ideas that seemed disjoint from the work found in the body of the paper.

Tianjin Polytechnic University, China: "Construct All-Electric Network"

This team from Tianjin Polytechnic University presented a strong approach to model the charging-station network-construction problem. They analyzed the present Tesla charging-station network connectivity in the U.S., stratified by type of developed human settlements, i.e., city, suburb, and rural. They concluded that the existing network has achieved the basic coverage throughout the country except for some small sites.

Based on the estimated total number of cars in each area and the average waiting time for car charging, they projected the number of supercharging stations needed. A multi-objective optimization model was constructed to compute the number of charging stations required in each region. The objectives were to minimize the cost as well as waiting time at the charging stations for each region, considering the three constraints for each region: the total travel distance supplied by the charging station should be greater than the actual power the vehicle needs, the total number of vehicles that the charging station can serve is greater than the actual number of vehicles, and the number of estimated charging stations required is greater or equal to the actual number.

To analyze the same problem for other developed countries such as Korea, the team established models to search for optimal charging-station locations so that the stations satisfy the charging needs for all nearby vehicles, considering the constraints of distance, time and traffic factors such as congestion index. An $n \times n$ weighted network map was constructed for each city/region, followed by proposed enhanced objective functions with an added new goal of shortest path. Their model constructions were distinct for city, suburb, and rural areas based on their different aspects.

To predict the growth rate of electric vehicles, the team exploited logistic regression models and suggested that the rate is associated with three indices: wealth distribution, policy orientation, and government investment. They also considered the impact of the number of chargers on the number of electric vehicles and of the distribution of the charger investment over time, then proposed a timeline for the full evolution to electric vehicles.

Intuitively, the team realized that the models proposed for the specific countries above could not be generalized; therefore, the team created a classification system based on the similarities between countries in terms of population density, GDP, country area, government investment, and electric vehicle price. They employed Mahalanobis distance to measure similarity between countries, then used a nearest-neighbor or single-linkage method to measure the similarity between classes. The judges found this idea to be novel: establishing a classification system to categorize counties into different classes and then developing the models for the most representative country within the class. However, the team did not go on to assess the impact of the dissimilarities between the countries within each classification on the prediction error generated by their proposed models.

The team introduced a clustering method for the site-selection problem. The centroid of the cluster, or selected site, was identified based on the shortest sum of the traditional shortest path location model. Here, they also introduced a congestion index to be one of the factors for the model. **Figure 3** is intended to illustrate the clustering results. This strong submission could have been even stronger if the image had included the clustering logistics and a label for the y-axis.

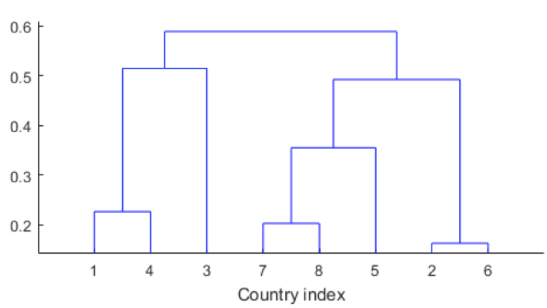

Figure 3. Tianjin Polytechnic University: Cluster diagram.

Xidian University, China: "How to Achieve the Full Adoption of All-Electric Vehicles"

This submission from Xidian University stood out to the judges for its innovative modeling approach, earning it the prestigious Euler Award. The team took a network-science approach, modeling the problem by a multilayer network whose nodes were the charging stations. While the edges were not clearly defined, the judges believed that edges connected two charging stations that were within battery driving distance from each other. This model could have been stronger if the team had placed an edge based on just a portion of the battery capacity, to give the driver flexibility in when and how often to charge. The paper also could have been stronger if the team had included a set of clearly stated assumptions; the judges had to make several inferences and add assumptions based on the paper's description.

The inner layer comprised charging stations within a county, mostly destination charging stations, whose count, number of locations needed, and their distribution over urban, suburban, and rural was computed. The betweenness-centrality identified locations to place the superchargers in this inner layer, and the team used an analysis similar to the destination chargers to divide them among urban, suburban, and rural areas. **Figure 4** presents these distributions as an example for U.S., taking into account different countries' standards. The outer layer comprised the charging stations between counties.

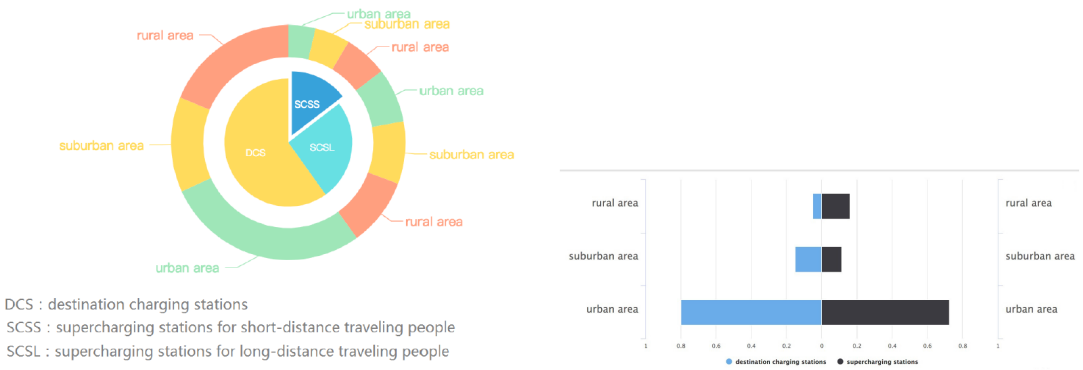

Figure 4. Xidian University: (a) The partition of charging stations and (b) the distribution between destination charging stations and supercharging stations for Tesla in the U.S.

Innovative to this paper was the idea of measuring the *level of satisfaction with the number of destination charging stations*, which the team defined as

$$\frac{\text{current number of destination stations}}{\text{total number of destination stations} \times \text{permeability}},$$

where the total number of destination stations was computed for when the country has gone all-electric, and permeability was the current proportion

of electric vehicles among all vehicles (electric and traditional). The same quotient, applied to superchargers, was used to determine the satisfaction with supercharging stations. A "satisfaction with location" formula was also created, similar to the previous one but more cumbersome.

The team used a diffusion model over the network to model the propagation of electric cars in the society, leveraging an SI (Susceptible/Infective) epidemic model based on the evaluation index system (SI-EI): the infected people were the ones driving electric cars, and the susceptible ones were the rest of the people. Following the directions of the tasks, the team applied their model to Tesla in the U.S., and then to Ireland. They considered three cases: building all the needed chargers in the city first, or in all rural areas, or a mix of both rural and urban. Particularly appealing was the approach that the team used to modify the SI model, taking into account new technology by using the SIS model, where some of the Infective (i.e., electric vehicle users) became Susceptible again by selling their electric vehicles due to vehicle-share, ride-share services, and Hyperloop. The impact of technology that would boost the spreading of electric vehicles was taken into account by modifying the λ parameter in the SI model, namely the daily infection rate. Sensitivity analysis, performed by varying λ, found that the model was less stable in the middle of the transition to all-electric, compared to the beginning and end stages of transition.

This team reported that the U.S. would have 8.1 million destination charging stations and 2.2 million supercharging stations in the final all-electric network, and that it would take 36 years to build it. They also identified that it would take a long time to get to full automobile electrification for this particular constructed network, namely, 108 years. Also, Ireland's network would have 78 thousand destination charging stations and 21 thousand supercharging stations in its final all-electric network.

The strengths of this paper are

- the nice executive summary that presents enough information for an executive to read;
- choosing a single model use for the whole paper, adjusting it as needed;
- bringing in an innovative thinking of measuring the level of satisfaction, and
- measuring the impact of technology by using the SIS model.

Judges always look for creativity in the submitted papers, and this paper, just like almost all submitted papers, could have been improved by

- bringing innovative ways of complementing the current ways of charging electric vehicles that could make the transition more attractive, and
- considering the impact of technology other than the ones suggested in the directions. The paper barely touched on the transition to larger vehicles, but it is good to see that the team thought about it.

Zhejiang Sci-Tech University: "Design of Elecomb"

This paper stood out to judges as Outstanding for several reasons: a creative approach, detailed results including a clear timeline and locations for a charging station network, and a more detailed analysis of new technologies and possible application of the model to any country. Their strong modeling and clear descriptions won them the additional distinction of the prestigious INFORMS Award.

Overall, the paper was well organized and easy to read, clearly walking the reader through the model development and results. All tasks from the problem statement were addressed, the variables were defined well, and the maps and flow charts added to the reader's understanding of both the modeling and the results.

The team began by determining that the U.S. will be able to fully supply drivers of electric cars with charging stations. In this first task, they used a common approach and fit the data with a linear model. The paper included a brief discussion of control engineering, but more details here on the method and outputs would have been helpful in conveying their approach.

The team continued with a creative and unique method for partitioning the U.S. into rural, urban, and suburban areas in a pixel-honeycomb shape, using the population and vehicle density of each region. They optimized the placement of charging stations with the constraints of both distance and cost. Additional supercharging stations were added by considering the highway system and placing stations every 50 miles along roads. While the judges would have liked to have seen more details about the costs and data to support this aspect, the model was outlined well, with excellent supporting figures, for example, **Figure 5**.

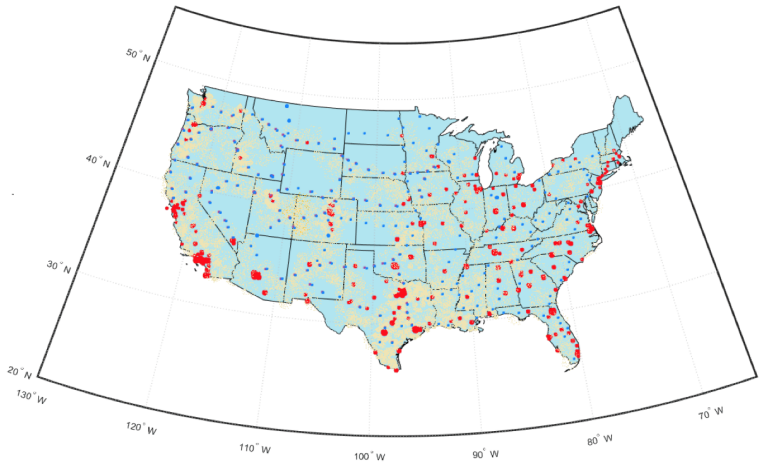

Figure 5. Zhejiang Sci-Tech University: Proposed distribution of charging stations in the U.S.

The established methods were then applied to Ireland with the addition of a metric to quantify the urgency of placing a charging station in a given location. This was a definite strength of this paper, since many teams did not give this level of detail for a plan and timeline for building charging stations. The accompanying maps, shown in **Figure 6**, conveyed the progression of the network by graphing the locations at three points in time.

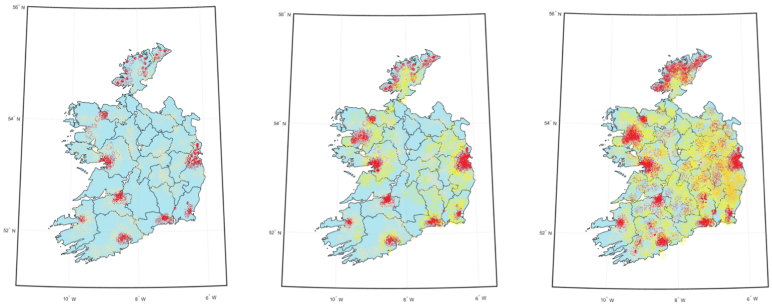

Figure 6. Zhejiang Sci-Tech University: The evolution of Ireland's car-charging network.

A final aspect of the paper that set it apart from other finalists was that it went beyond the discussion of ideas to giving very specific recommendations supported by some analysis. Two examples of this were seen in the later sections of the paper:

- The first was the index created to aid counties in developing a plan for constructing charging stations. Most papers very broadly discussed ideas for planning in other countries; few implemented them in a given formula. This paper included an index that had specific inputs such as population, land area, Gini Index, as well as others, that output whether the network should build in rural, urban, or a combination of areas first.
- The second was in the team's discussion of the impact of new technologies, specifically rapid battery-swap stations. They provided plots to show how many fewer stations would be needed in both the U.S. and Ireland following adoption of this new technology.

The paper concluded with a brief list of strengths, weaknesses, future work, and conclusions. There appeared to be a sensitivity analysis on the urgency Indicator. Many papers do not address possible variations in input values. While the inclusion of a sensitivity analysis was a strength, a more detailed discussion would have made the paper even stronger.

The handout for Task 5 was strong example, in that it gave a graphic and clear steps for a country to take to determine a building plan. Unlike many papers that had targeted handouts, this team produced a handout that was generalized so that any world leader would be able to determine their charging-station development plan. While the handout included a clear description for a simple calculation, it was not stand-alone as intended, since it relied on the formula and variables from the body of the paper that were not included on the handout.

The judges suggested three areas for improvement in the paper, in the executive summary, citations, and model assumptions:

- The executive summary was strong in that it gave specific details and model outputs; however, it did not briefly restate the problem so that this one-page summary could stand alone.
- A second area for improvement is the use of citations. The paper lacked in-text citations and had a fairly limited set of references listed.
- Finally, the assumptions were limited, since they can change; but they need to be clearly stated and justified. For example, in creating the station network for Ireland, several simplifying assumptions were made, such as not considering suburban areas and a maximum travel distance of 100 miles. These should have been explained with relevant data and discussion to support and validate them.

Despite these areas for improvement, the judges agreed this paper was a very strong submission.

Conclusion

Through the process of triage and final judging, the pool of 3,158 Problem D submissions was reduced to 11 finalists, which led to some excellent discussions as we selected this list down to the six Outstanding papers. Throughout our discussions, it was clear that no submission was perfect: Some had stronger writing, others had more creative models, and still others did a really great job of tying their mathematics to the real world through their modeling. Some papers focused more on one task than another. Ultimately, the judges were surprised by all that the teams did in the span of 98 hours, and we look forward to seeing what next year's teams will do!

About the Authors

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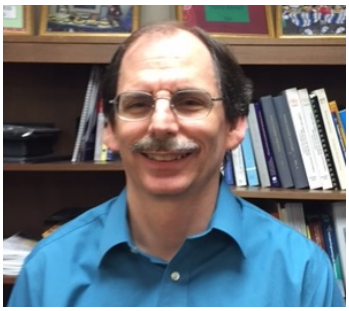

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